THE DEVELOPMENT OF HYDRO-ELECTRIC POWER STATIONS

BROWN, BOVERI & COMPANY

LIMITED

BADEN (SWITZERLAND)

871 E — II. 2

July, 1926

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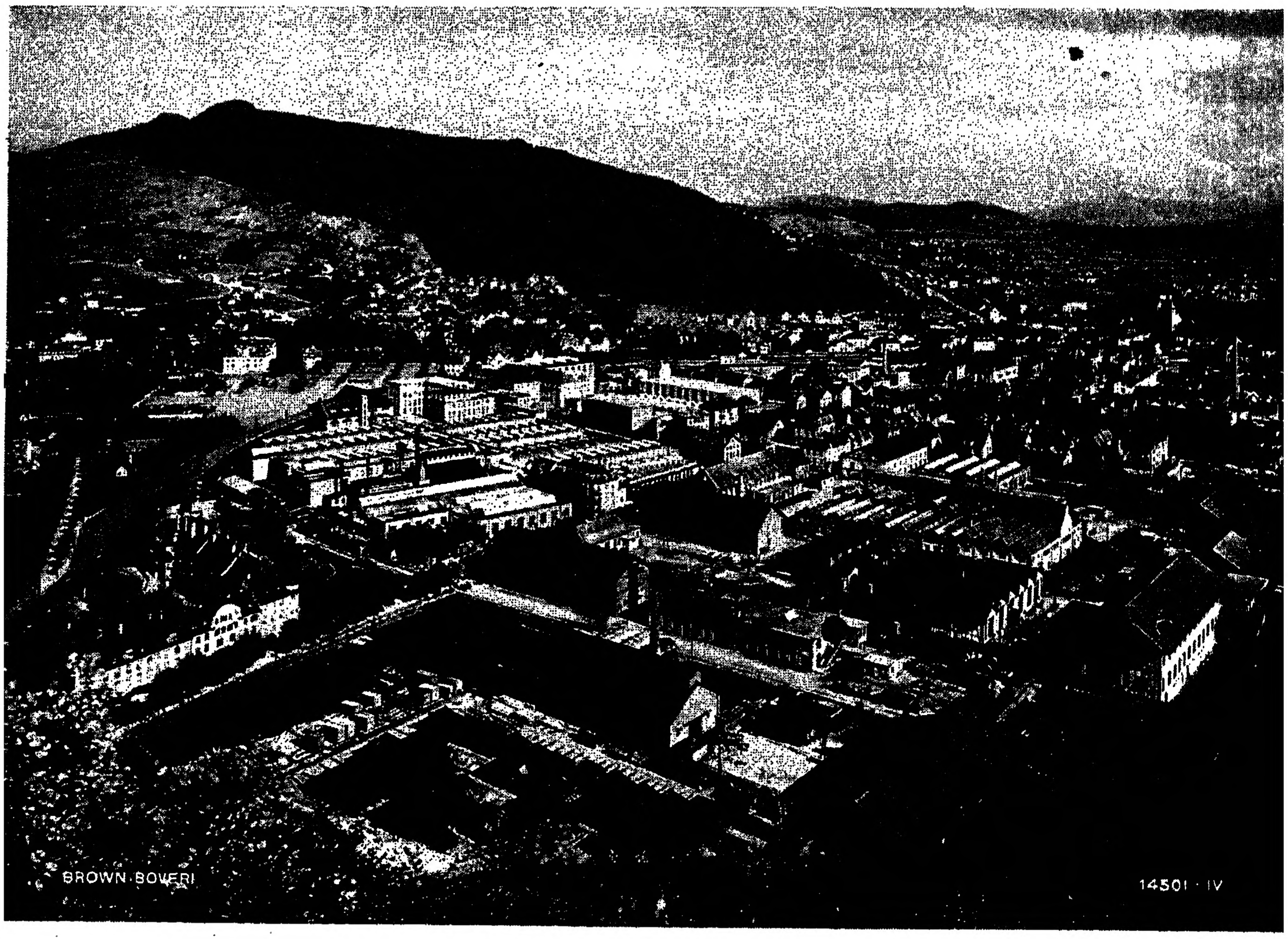

The Brown Boveri Works, Baden, Switzerland.

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THE DEVELOPMENT OF HYDRO-ELECTRIC POWER STATIONS

1. INTRODUCTION.

For many centuries, water-wheels satisfied all demands for the use of water power, and, indeed, many examples of them still exist in out-of-the-way valleys, where they are used as the prime movers for small saw-mills, etc. Although a simple water wheel of correct design could work with an efficiency as high as 80%, nevertheless great improvements were necessary before the Pelton and Kaplan turbines as installed in modern power stations were developed.

Perhaps the most memorable year in the history of electrical technology was, 1891, as, in connection with the Frankfort Exhibition, energy was first transmitted over a great distance. The line between Lauffen and Frankfort, a distance of 175 km, was supplied with three-phase current at 25,000 volts[1]. This operation, which proved the possibility of transmitting electric energy economically, was of outstanding importance in the development of hydro-electric stations. The results of the experience with the transmission plant between Lauffen and Frankfort were applied practically on a large scale a few years later in the power transmission station at Rheinfelden. It was shown that it was no longer necessary to produce power where it was utilized, but rivers away from the centre of supply could be employed for producing electric energy. Owing to the easy way in which electric energy could be distributed, it soon became possible to produce the energy in a few large stations, thus increasing the output per station and allowing more economical operation to be obtained. This trend of development in hydro-electric stations continually demanded machines of increased output. The turbine designer had to consider the utilization of very large volumes of water and high heads, while alternators had to be made for generating large currents at the highest possible pressure.

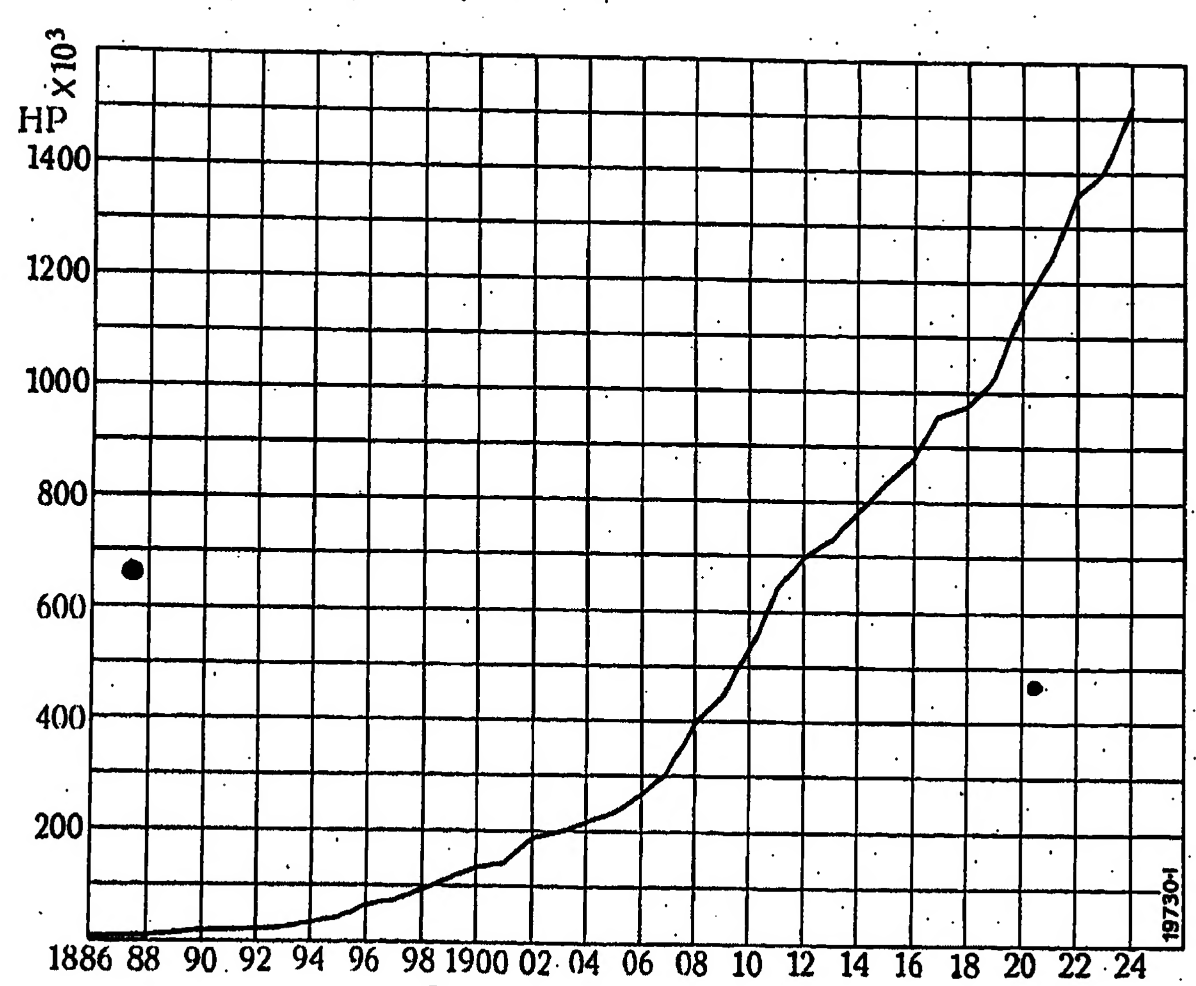

Fig. 1.
The development of the use of water power in Switzerland.
(From the "Guide to the Swiss Hydraulic Developments").

As electricity was rapidly adopted for industrial, commercial, and household purposes, it became economically important to use the water power available. Fig. 1 shows the growth of the electric energy developed in Switzerland.

It is clear that this increase in the use of water power was only rendered possible by the great development of the machines, both on the part of the makers of the hydraulic turbines and also of the electrical generators. Brown, Boveri & Co. can claim the honour of being among the pioneers of water power development. Right at the start they were in a position to supply the necessary electrical generators, of proved and reliable constuction, as well as high-grade transformers, motors, and other equipment for the economical distribution and application of the power produced.

[1] The machines were designed by Charles E. L. Brown, who was one of the founders of Brown, Boveri & Co.

2. WATER TURBINES

This brochure deals more particularly with the electrical equipment of hydro-electric power stations than with the water turbines, but, in view of the fundamental influence which the hydraulic part exerts on the general layout of the plant, it appears to be essential that the chief properties of water turbines be mentioned.

The types of turbine in general use to-day are the Francis or reaction turbine and the Pelton or impulse turbine.

Francis turbines are divided into three classes according to their specific speeds, viz., low, normal, or high-speed. High-speed turbines are used with low heads down to about 0·5 m and low-speed turbines for the highest heads, up to about 300 m. Both deviations from the normal-speed type tend to result in a decrease of the efficiency; this is more noticeable with high-speed turbines. The endeavour to maintain the largest unit output possible for low-head turbines became a struggle for attaining higher efficiencies by means of higher specific speeds. Within the last decade this has led to the Francis turbine being developed into various new types e. g., the propeller type (Kaplan and Lawaczeck), and the screw type (Theodor Bell & Co.) which attain specific speeds of 500—1000[1], while the previous limit for the Francis type turbine was 450. These turbines have efficiencies up to 90 % on full-load. The typical characteristic of a Francis turbine shows a large drop in the efficiency at partial loads, but, by the use of adjustable runner blades, Kaplan has avoided this drop and hence there is only a comparatively small change in the efficiency between one-quarter load and full-load.

Francis turbines are used exclusively for low-pressure stations (up to 15 m), as they require the largest volume of water with comparatively small heads. On the contrary, for high-head stations (over 300 m) only Pelton turbines can be considered as they have a smaller specific speed, because with such heads Francis turbines would run at inadmissible speeds. For heads between these values either one or the other type may be used, according to the special conditions. For small volumes of water, Pelton turbines are the more advantageous, but for large fluctuations in head, Francis turbines which use the total head are employed, as with the impulse turbine a loss of head of two metres arises between the lower edge of the impeller and the tail race. Francis turbines are also used in high-head stations (with falls of 300 m) on account of their higher speed which enables cheaper generators to be employed. As already mentioned, hydro-electric stations may generally be divided into three classes, viz., low-head stations (falls up to about 15m), medium-head stations (falls up to about 50 m) and high-head stations (falls of over 50 m). The limits are not sharply defined, but the division is approximately retained.

Low-head stations are characterised by the fact that the machine room almost forms part of the dam, as well as by the fact that the turbines are installed in ducts and have no casing. In medium-head and high-head stations, the turbines are invariably provided with a casing. Francis turbines made with barrel casing are suitable for low-heads. The volute casing is becoming more and more generally employed as it enables the water to be used to greater advantage.

Fig. 3 shows a typical example of a low-head station, for which Brown, Boveri & Co. delivered all the electrical equipment. Fig. 4, on the contrary, shows a modern high-head station for which Brown Boveri supplied the alternators and also erected the complete hydro-electric sets shown in Fig. 5.

A good idea of the above-mentioned increase in unit output of water turbines since 1892 is given by Fig. 6, which shows the largest hydro-electric sets for which alternators of Brown Boveri manufacture have been supplied.

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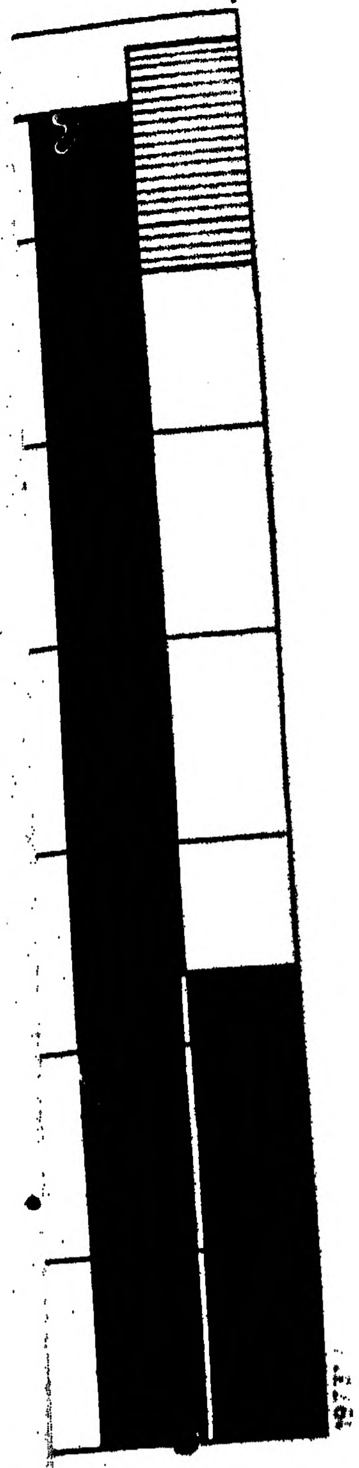
[1] The specific speed n_s is constant for a series of geometrically similar turbines and can best be defined as the speed of a turbine of a typical series, which develops 1 H.P. with a head of 1 m.

$$n_s = \frac{n}{H} \sqrt{\frac{L}{\sqrt{H}}} \qquad \text{if } n = \text{real speed},\ H = \text{head in metres},\ L = \text{effective output in H.P.}$$

The following are typical values of n_s:

Pelton turbines	10–30
Francis turbines	30–450
Propeller and screw turbines	450—1000

For high heads n_s may be less than 10 if Pelton wheels are used. The turbines in the Fully Power Station (Vaud) with the highest head in the world (1650 m) are built for a value of $n_s = 2{\cdot}7$, in order to reduce the runaway speed as much as possible.



Siebnen	Rempen	Vernayaz Swiss Fed. Rlys.
4	4	6 (5)
6000	66000	69000
3	3	1 3
500	500	$33^1/_3$
8000	8000	15000 10000
50	50	$16^2/_3$ 50
195	250	630
Francis	Francis	Pelton
1	1	6
1924	1924	1926

va.

The economic considerations of the complete installation are decisive when choosing the output per unit, the speed, and the arrangement of the machines. Large unit outputs simplify the turbines and the leading in of the water; hence they tend towards cheaper foundations and smaller machine rooms. A considerable saving of material both in the turbine and alternator, can be effected if high speeds are used. The limiting of the unit output results, for each individual case, from the consideration of the probable service conditions (temporary variations of the water supply and of the demand for current). If, in an exaggerated case, the total hydraulic power were converted to electric energy by one single set, the complete station would be shut down during overhauls or repairs to any one part. There is always a limiting output which it would not be economical to exceed with the existing manufacturing and transport facilities. The ever increasing speed is limited only by the strength of the material. The runaway speed is the deciding factor when fixing the dimensions of the rotating parts. This is the speed at which the turbine would run if the governor failed to operate when the machine was entirely without load.

An important question is the decision of the type of alternators to be used—whether

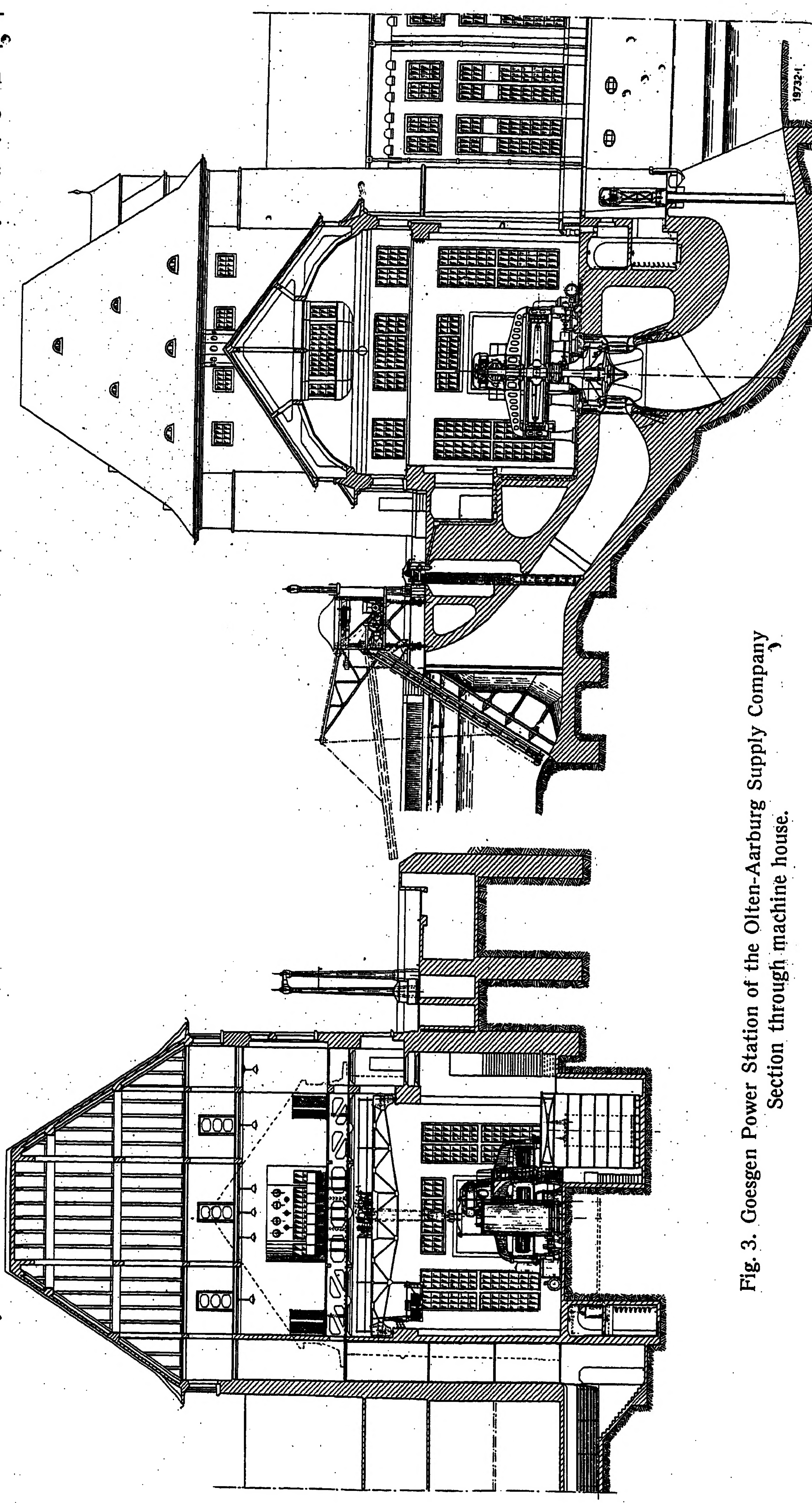


Fig. 3. Goesgen Power Station of the Olten-Aarburg Supply Company
Section through machine house.

they shall be built with vertical or horizontal shafts. The horizontal-shaft types have the advantage that the hydraulic and electric machines are installed on the same floor and are able to be moved, independently of each other, by the machine-house crane. It is necessary to use the vertical-shaft type in some special cases, as for example, if the head is very small or varies greatly, or if the machine room floor has to be raised above the high-water level. It may be mentioned that since they introduced the vertical-shaft machine, Brown, Boveri & Co. have devoted special attention to this type of installation and Dr. C. E. L. Brown designed the so-called umbrella type of generator.

Difficulty in supporting the very heavy rotating masses was at first encountered with very large vertical-shaft machines. However, the thrust bearing having a perfect action with large loads at high speeds was subsequently built, and there is now nothing to prevent the construction of large vertical-shaft units.

Brown, Boveri & Co. have taken

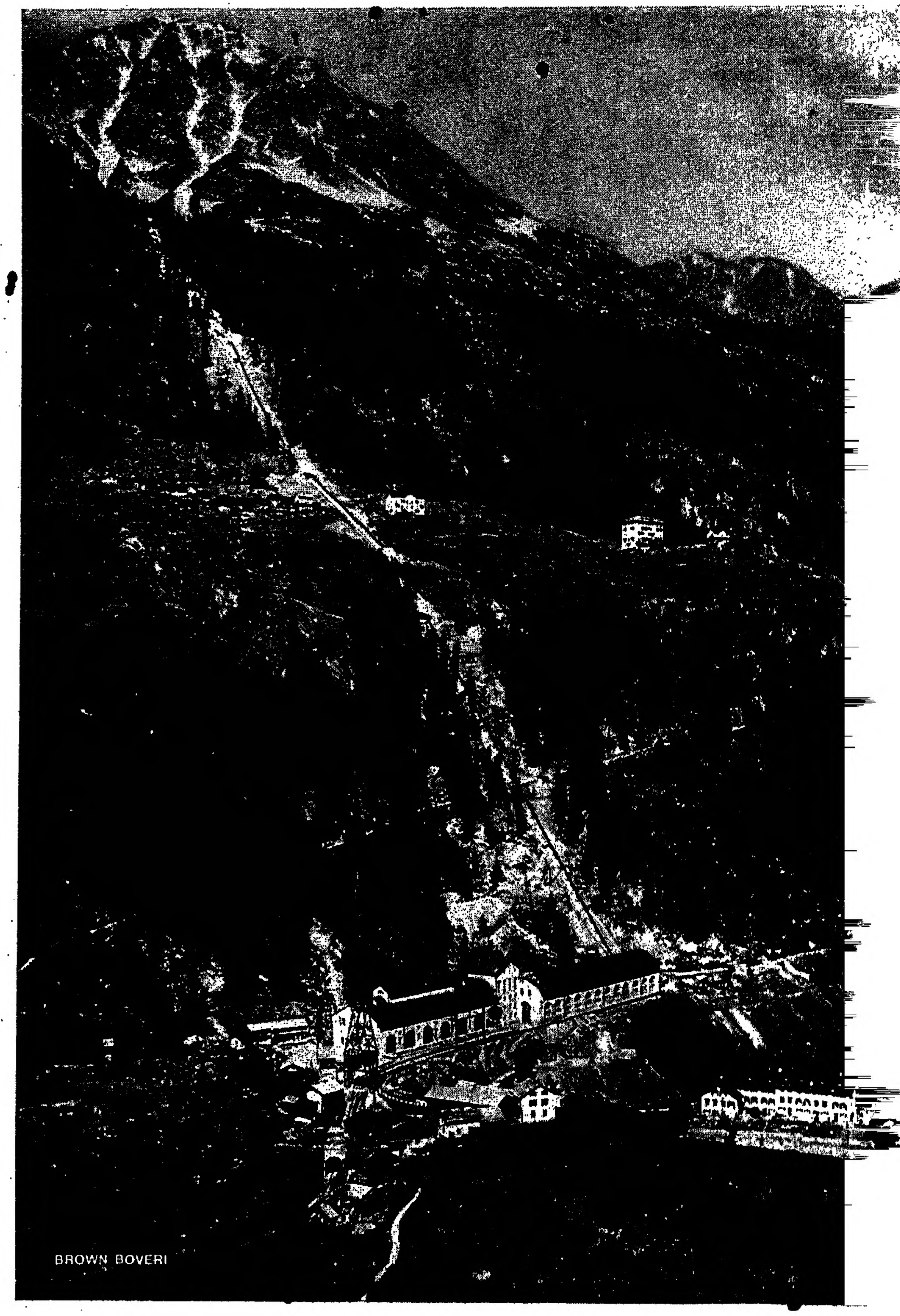
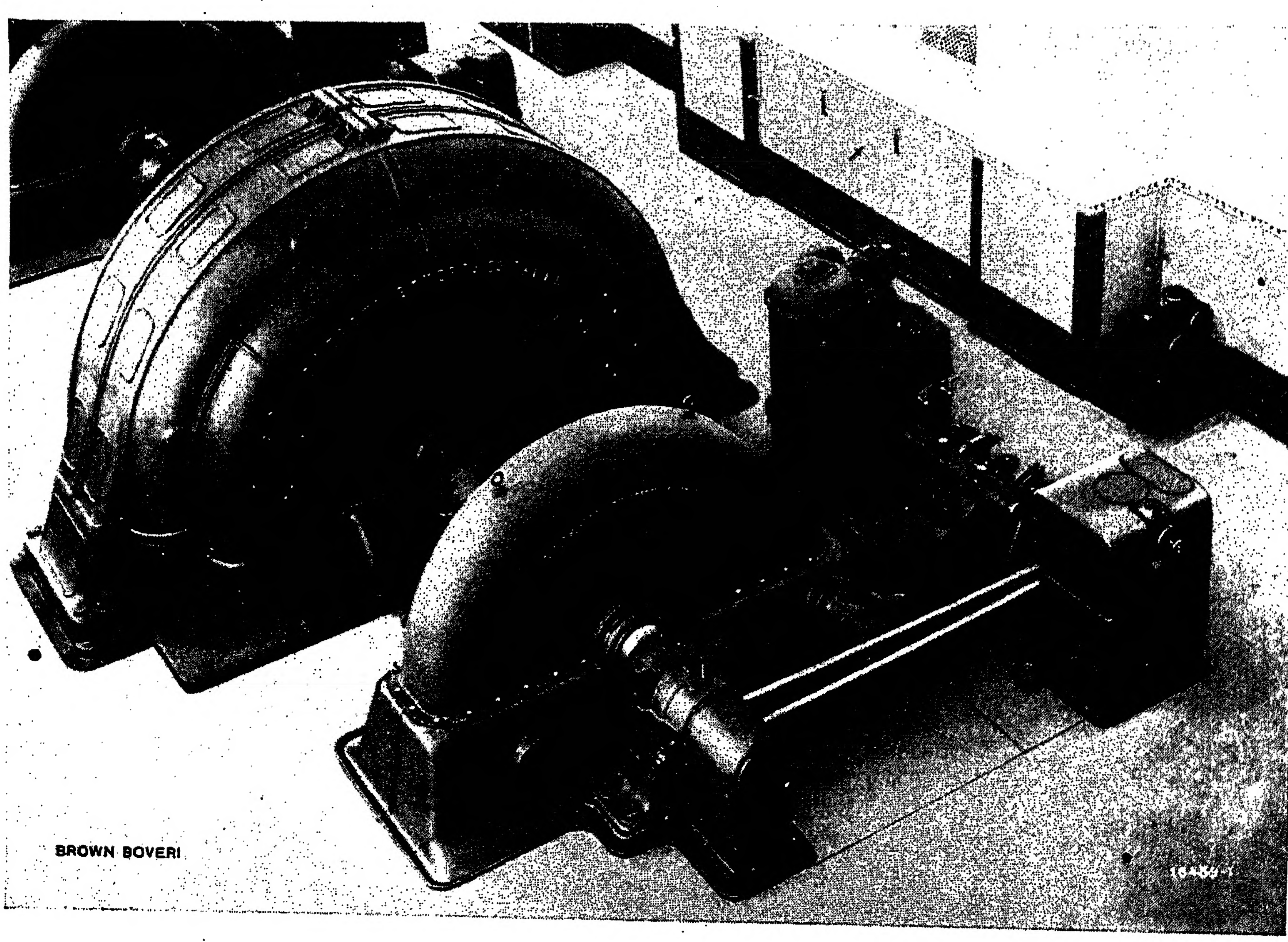


Fig. 4. Barberine Po[w]
Station of the Swiss Fe[d]
Railways.



an active interest i[n the] development of the [mo]dern thrust bearing[;] have produced a sup[erior] type of bearing wit[h seg]ments which are [auto]matically adjusted [and] lubricated. On accou[nt of] the higher specific l[oad]

Fig. 5. Part of the ma[chine] room of the Barberine P[ower] Station of the Swiss Fe[deral] Railways, containing t[he] single-phase alternators for 10,000 kVA, 333 1/3 r.[p.m.] 15,000 V, 16 2/3 cycles

allowable with this bearing, the dimension are far smaller than was possible with previous designs. A detailed description of this thrust bearing (Fig.7) was published in the Revue BBC, 1917, Nos. 1—4; the various designs have proved to be so good that Brown Boveri thrust bearings have been provided for machines which were already installed and which were not supplied by the firm.

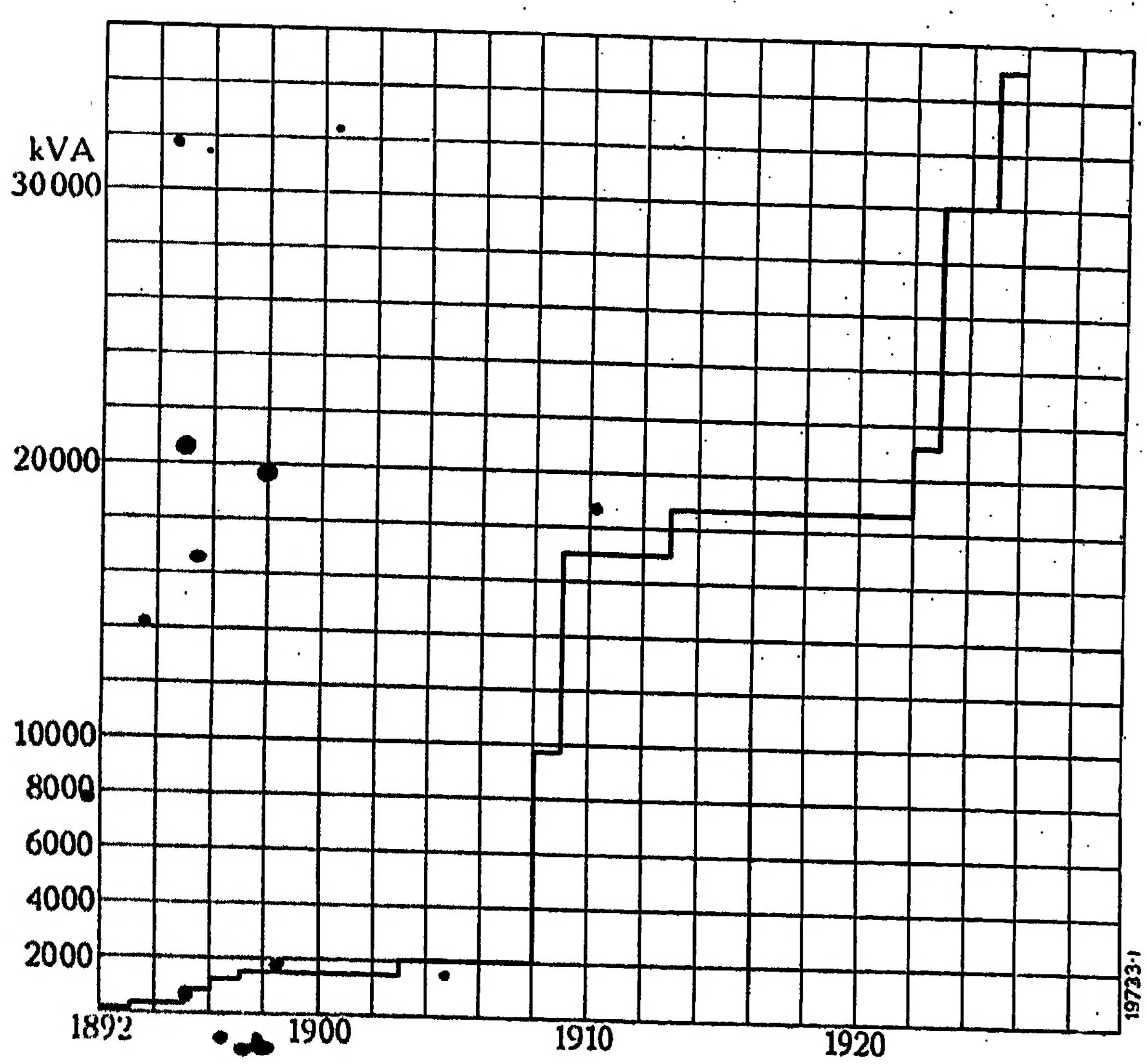


Fig. 6. Development of the unit output of alternators driven by water turbines.

Objection to very large vertical-shaft machines was no longer reasonable, and hence they are now not only used in low-head, but also in medium-head and high-head stations. Besides the increased speed, a decisive factor in most cases is the saving of floor space in the machine room. This saving in building costs more than compensates for the fact that vertical-shaft alternators are initially more expensive if compared with machines of the horizontal type. A circumstance which may have influenced the use of horizontal-shaft machines in low-head stations until now, was the limited capacity of the previous Francis turbines. For large volumes of water it was necessary to employ multiple turbines (with several runners mounted on the same shaft). With low heads it was often impossible to mount the various runners one above the other, hence the horizontal type presented a solution. The Augst Power Station, which is equipped with generators supplied by the Alioth Electrical Co. (now Brown, Boveri & Co.), is a typical example of this kind of installation (Fig. 8). Improvements in turbine design, which have led to the modern propeller and Kaplan turbines with very large capacities, have raised the upper limit of the volume of water supplied to one runner, so that it is no longer necessary to abandon the vertical-shaft type if it proves to be suitable in other respects.

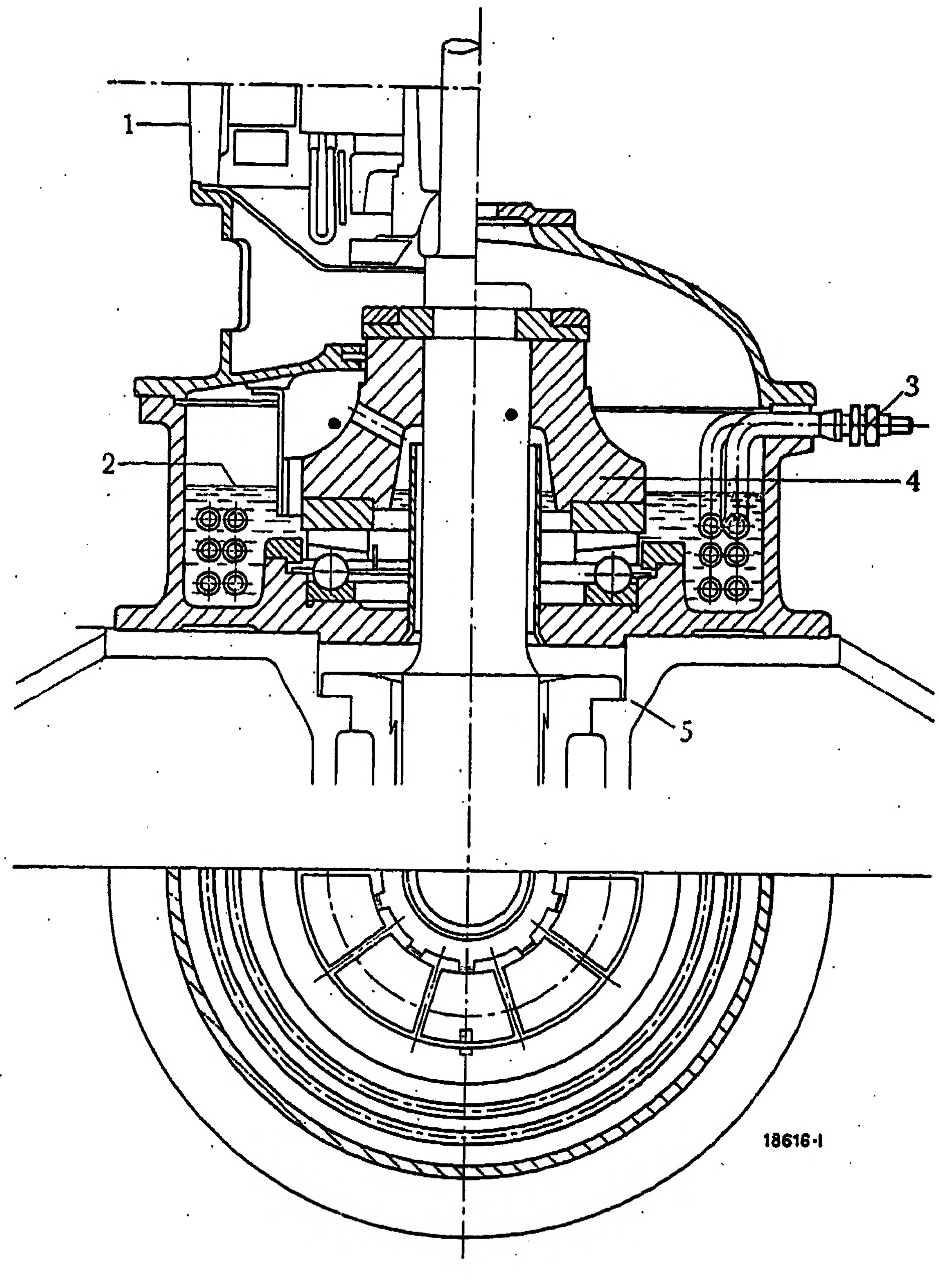
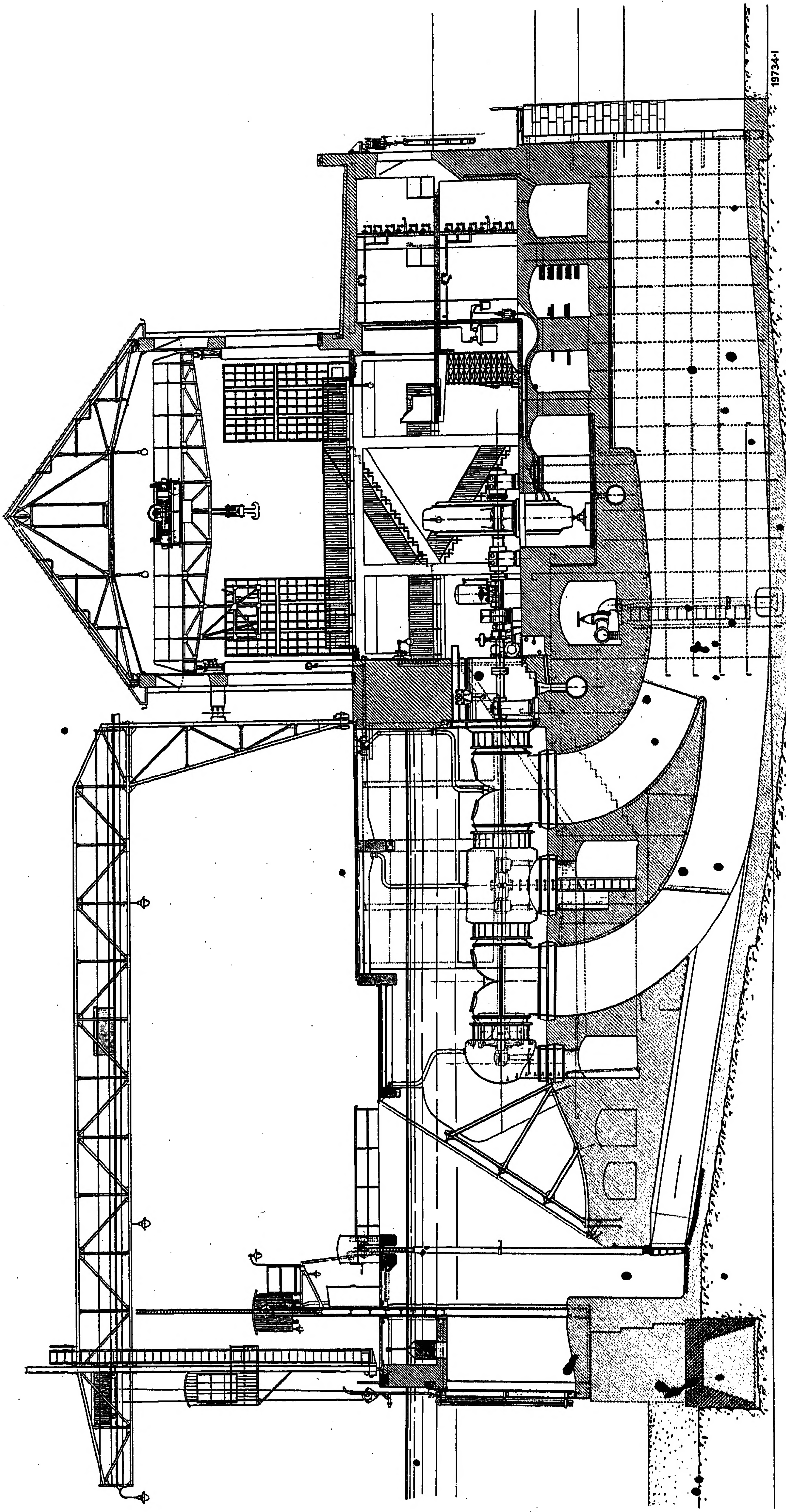


Fig. 7. Segmental thrust bearing for 350 tons at 100 r. p. m.
1. Exciter. 2. Oil level. 3. Cooling water inlet and outlet. 4. Thrust block. 5. Alternator.

The system supplied by the hydro-electric station requires that the frequency and pressure be kept as constant as possible; hence it follows that the hydraulic prime mover must run at a constant speed on all loads, or during any fluctuations of load. If the output required from a set suddenly decreases, it is natural that the large torque of the turbine leads to an increased speed. When this occurs, the turbine governor, by means of hydraulic relays and a servo-motor, must reduce the primary torque

by altering the admission as soon as possible, until a balance of power is once more established. When the speed is once more at its normal value, the regulator comes to rest. If the load reduction is so great that the turbine is shut down, it is clear that the kinetic energy of the water in the supply lines must be absorbed in some way, as it is braked by the sudden closing. The kinetic energy appears as a sudden pressure rise in the pipe line. The pressure rise for equal leads is directly proportional to the length of the pipe and inversely proportional to the diameter. Under certain conditions this water hammer may cause dangerous fluctuations which may lead to damage in the pipe line, etc. The water mains must therefore be suitably dimensioned or the closing time of the regulator prolonged so that no danger can arise. Another solution consists of equipping the turbine with a pressure regulator, which allows a quantity of water to flow out through a by-pass to avoid the pressure rise previously mentioned; hence the velocity conditions in the pipe line remain unchanged. With Pelton or impulse turbines, by the



use of a deflecting nozzle, or more simply, by means of a deflector, the pressure regulator can be connected to the speed regulator in the simplest possible way.

3. ALTERNATORS.

After what has previously been stated it is perfectly clear, that in a hydro-electric station considerations of the total cost of the plant, and in particular the cost of the hydraulic installation, determine the kind of equipment chosen.

On the electrical side, the use of large power units led to the choice of the highest possible pressures for the generators in order to obtain economical transmission of the power. Fig. 9 shows the increase of the pressure for alternators built by Brown, Boveri & Co. Of all firms, Brown, Boveri & Co. established a lead, and since 1909, have built machines for a service pressure of 16,000 V. The experience obtained during the 17 years since then has been so favourable that an ever increasing number of power stations are being built for this pressure.

After deciding whether vertical or horizontal machines will be installed, and the output per unit, there are still many questions which require the turbine builders and the alternator manufacturers to co-operate.

The manufacturers of the turbine must naturally build a machine for the speed which corresponds to synchronous speed of the predetermined frequency. The generator, on the other hand, must be dimensioned so that it can withstand the centrifugal force occurring at the runaway speed of the turbine. With the types of turbine usual up to the present, the runaway speed is about 1·8 to twice the normal speed. This increase in speed can be taken into consideration without excessive difficulties. With extra-high-speed machines (propeller or Kaplan turbines) the difficulties are increased, as the runaway speed is 2½—3 times the normal speed. The existing types were no longer suitable for the forces set up, hence expensive alternators of special design were necessary. It is not improbable that further development will take place in this direction by employing the same rotor construction for hydro-electric generators as Brown, Boveri & Co. successfully introduced for turbo-alternators.

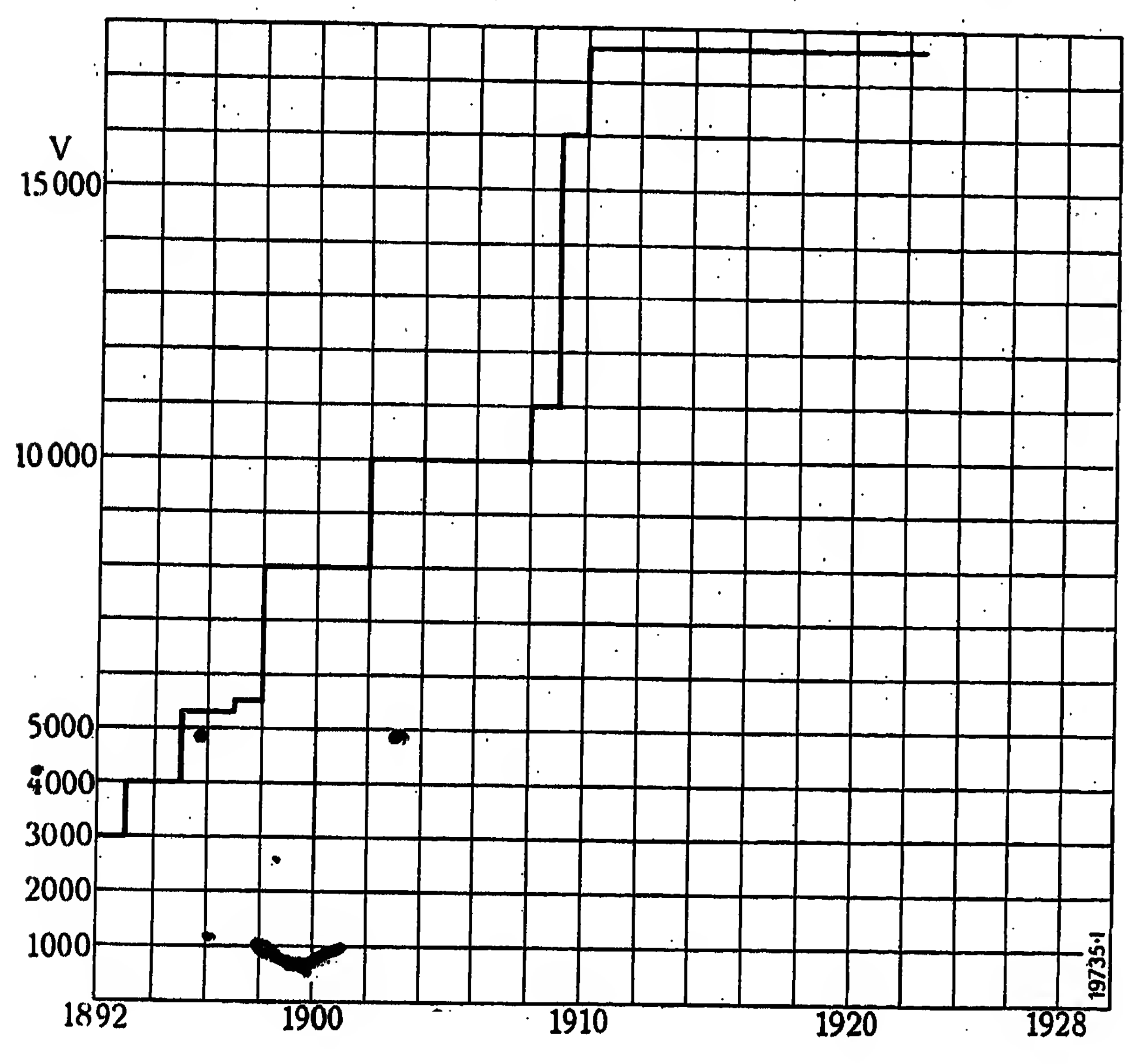


Fig. 9.

Increase of machine pressure for water-driven alternators.

Considerations of economy in hydro-electric stations will lead, therefore, either to develop turbine regulators to such a degree of reliability that failure to operate is impossible, or it will be necessary to reduce the runaway speed of the water turbine by some other means. Until this problem is solved, there is nothing that can be done other than to make the alternators safe against the centrifugal forces by the use of suitable types and good quality material. Serious disasters can arise from the non-observance of these requirements — in fact accidents have already taken place; this clearly shows that the generators for the construction of a power station should only be ordered from

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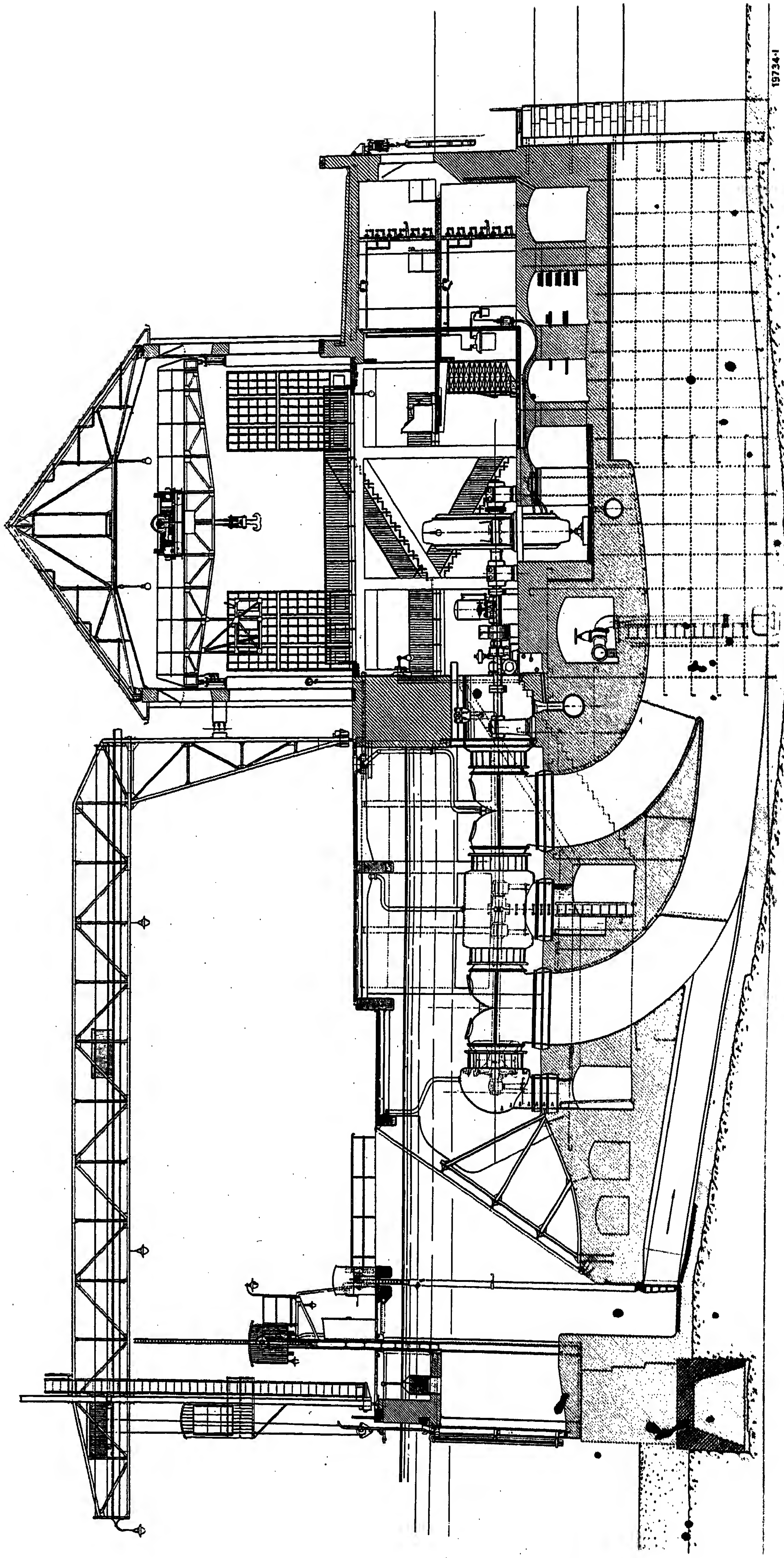

Fig. 8. Cross section of Augst Power Station, Basle.

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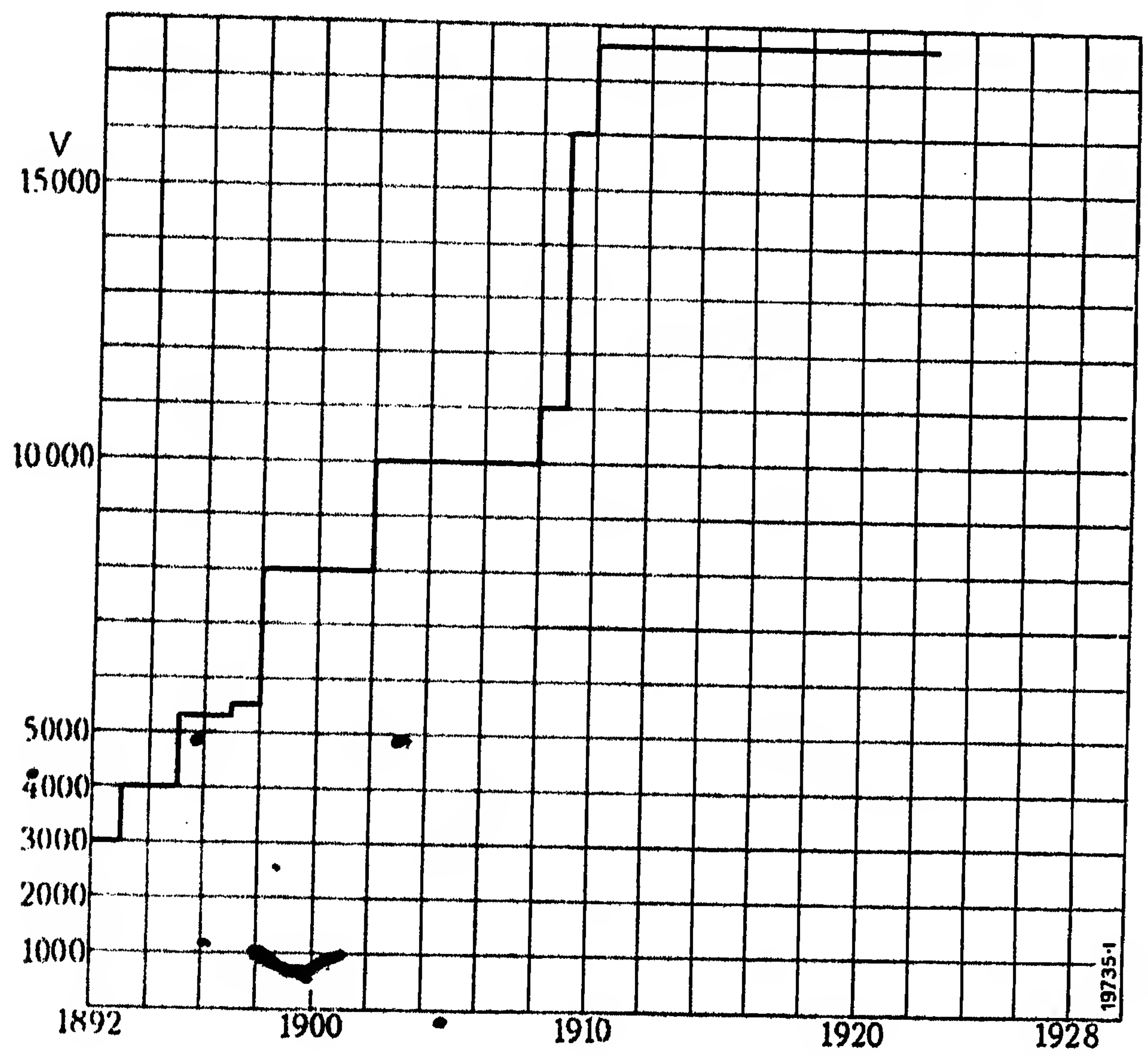


Fig. 9.

Increase of machine pressure for water-driven alternators.

a firm whose experience and plant can offer full guarantees regarding safety from the action of centrifugal forces. Brown, Boveri & Co. have always manufactured machines which will be suitable for the runaway speed given by the manufacturer of the turbine. The properties of the material to be used for the highly stressed parts of the rotor are tested in a scientific manner in the firm's own material testing laboratory, both before and during the machining. Completed rotors are tested, at the runaway speed of the turbine, on the over-speed test bed. A full description of this plant appeared in the Revue BBC, 1917, No. 12. Fig. 10 shows the over-speed testing pit for vertical-shaft rotors.

The constructor of the alternator must take into account a further point, which is still less known, in connection with the conditions imposed by the hydraulic portion of the installation. As shown in section 2, the speed variations which really occur with the load changes are smaller the quicker the turbine governor operates. They are also inversely proportional to the moment of inertia of the rotating parts, which are normally calculated as the flywheel effect, WD^2, giving a value equal to four times that of the moment of inertia. With a predetermined allowable speed variation the flywheel effect of the moving masses may be smaller, the quicker the governor operates. As the design of the turbine offers scarcely any opportunity to increase the flywheel effect, this matter must be adjusted in the rotor of the electrical part. This often leads to dimensions of the rotating parts of the alternator which are far in excess of those required for strength and consequently produces heavy and also expensive electric machines. By including larger rotating masses than would result in the usual types, the dead weight of the alternator, i.e., the weight of the material not necessary for the production of the electric energy, is greatly increased. Thus the cost of energy per kVA when this type of alternator is used will be found to be appreciably higher than that of an alternator of standard design, but the price per unit weight will be found to be lower. When comparing various offers for alternators the flywheel effects must be considered; they cannot be overlooked as frequently happens. The above remarks show that the builder of a power station may obtain cheaper and more economical machines by employing regulators which act in the most rapid manner possible. As shown in section 2, the closing time of the regulators must increase with the length of the pressure line and the reduction of its diameter; it therefore follows that, retaining the output and speed, the flywheel effect of the set must be larger, the smaller the diameter of the pipe line and the greater its length.

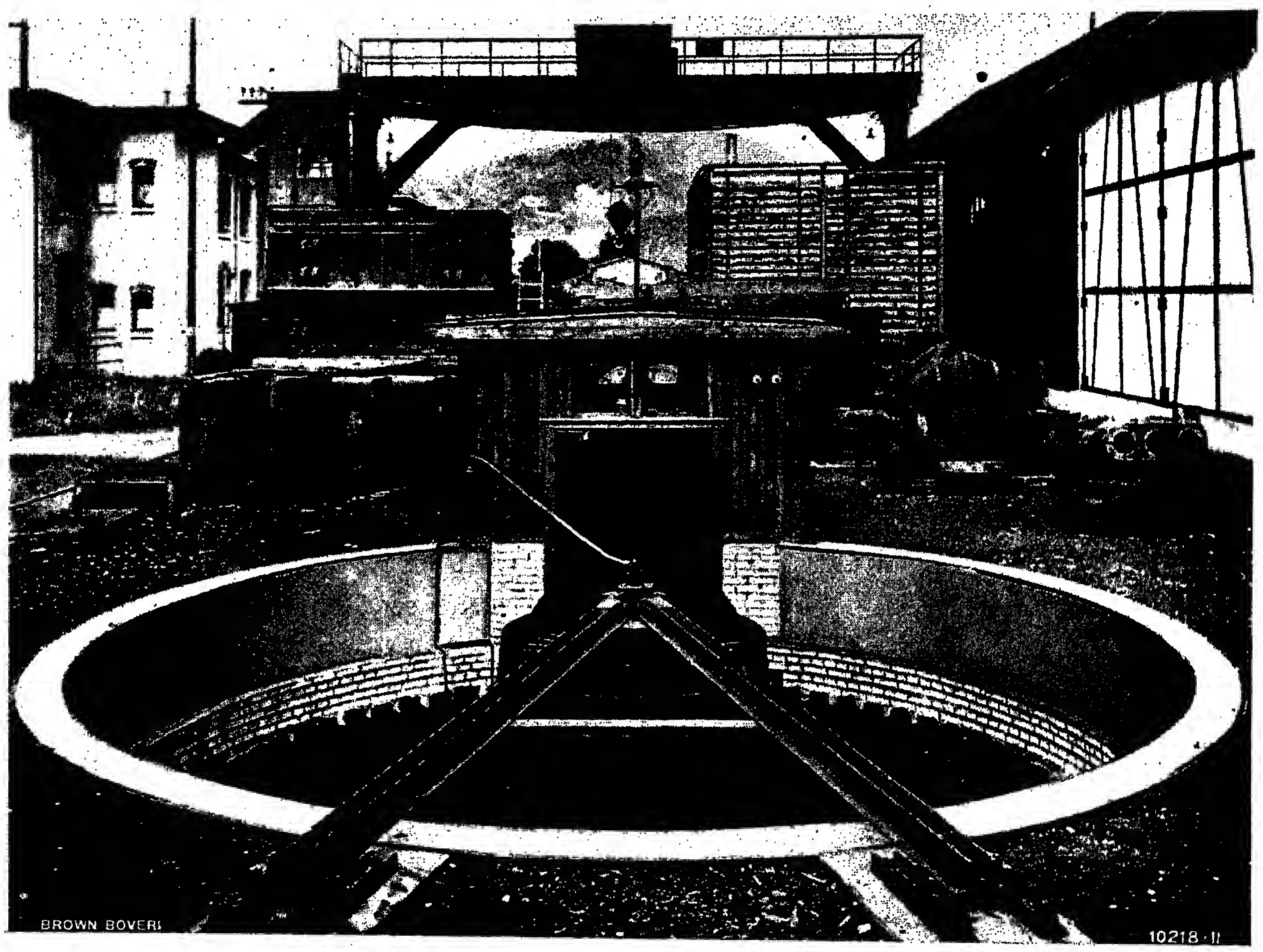


Fig. 10.
Over-speed test pit for vertical-shaft rotors.

The mounting of large masses in the rotor often produces considerable constructional difficulties, particularly if the high runaway speed compels the diameter to be reduced in order to avoid too great a peripheral speed. In certain cases it is often possible to secure a flywheel rim to each side of the pole wheel in

order to obtain the required effect, but often the only solution is to provide a special flywheel (Fig. 11). However, an increased number of bearings is necessary with this arrangement; it also involves greater bearing and air friction, and has the disadvantage of occupying a great deal of floor space. These conditions, however, can only be altered by changes in the hydraulic parts. It is clear that, for the design of a hydro-electric station, the co-operation between the expert adviser for hydraulic plant and the builder of the electric machines is important and necessary from the commencement of operations. In many cases it may be recommendable to give the complete development of the power station to one firm of specialists (similar to Brown, Boveri & Co.), who have had very wide experience in the construction of power stations, and have a skilled staff at their disposal.

With direct coupled hydro-electric sets various other questions arise, which, although they are not of primary importance, must nevertheless be considered. The spider supporting the thrust bearing of vertical-shaft sets, for instance, must be dimensioned for the weight of the turbine runner and also the axial thrust imposed upon it by the water pressure; with horizontal-shaft sets consideration must be given to the stresses set up in the shaft by the turbine being overhung, and the admission of water to only one side of the runner when dealing with Pelton wheels.

As with all other processes for converting energy from one form to another, an electric current cannot be produced without generating heat, caused by copper and iron losses, friction with the air and in the bearings, etc. The manufacturer must so design his alternator that the heat generated may be led away before any part of the machine attains a dangerous temperature. Cooling problems occur with all electric machines, but with alternators for large outputs they assume a special importance. Contrary to transformers, only air may be used for cooling generators. The method of supplying the air for the generators has undergone various changes, which, as is generally known, have had a considerable influence upon the design of the power station. The generators were formerly of the protected type, without exception. The fans mounted on either end of the rotor caused the air to be drawn in axially from the machine room; it was then thrown radially outwards, passing over the windings, and returned to the machine room through the cooling ducts in the stator and the openings in the frame.

The alternators at the Goesgen Power Station (Fig. 12) are of this type, and are remarkable on account of their large output per unit and their special construction. They are mounted on pedestals so that all parts are accessible from the machine room floor. This solution of the cooling problem is the cheapest, as no ducts are needed for leading away the air. Nevertheless, with large units serious disadvantages accompany this method of cooling; for example, the heating of the air of the machine room is likely to be particularly

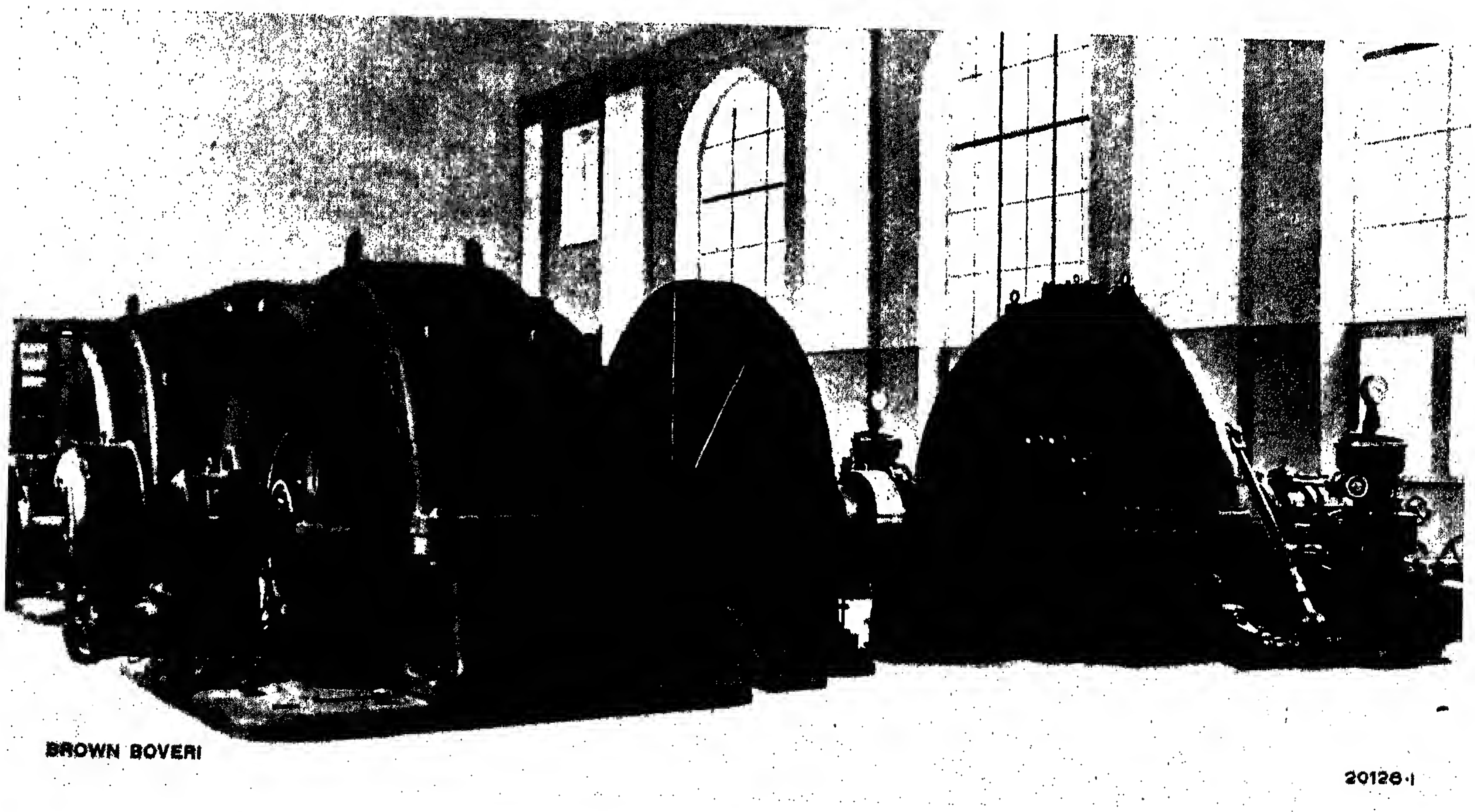


Fig. 11.
Example of hydro-electric set with flywheel, at Massaboden Power Station of the Swiss Federal Railways.

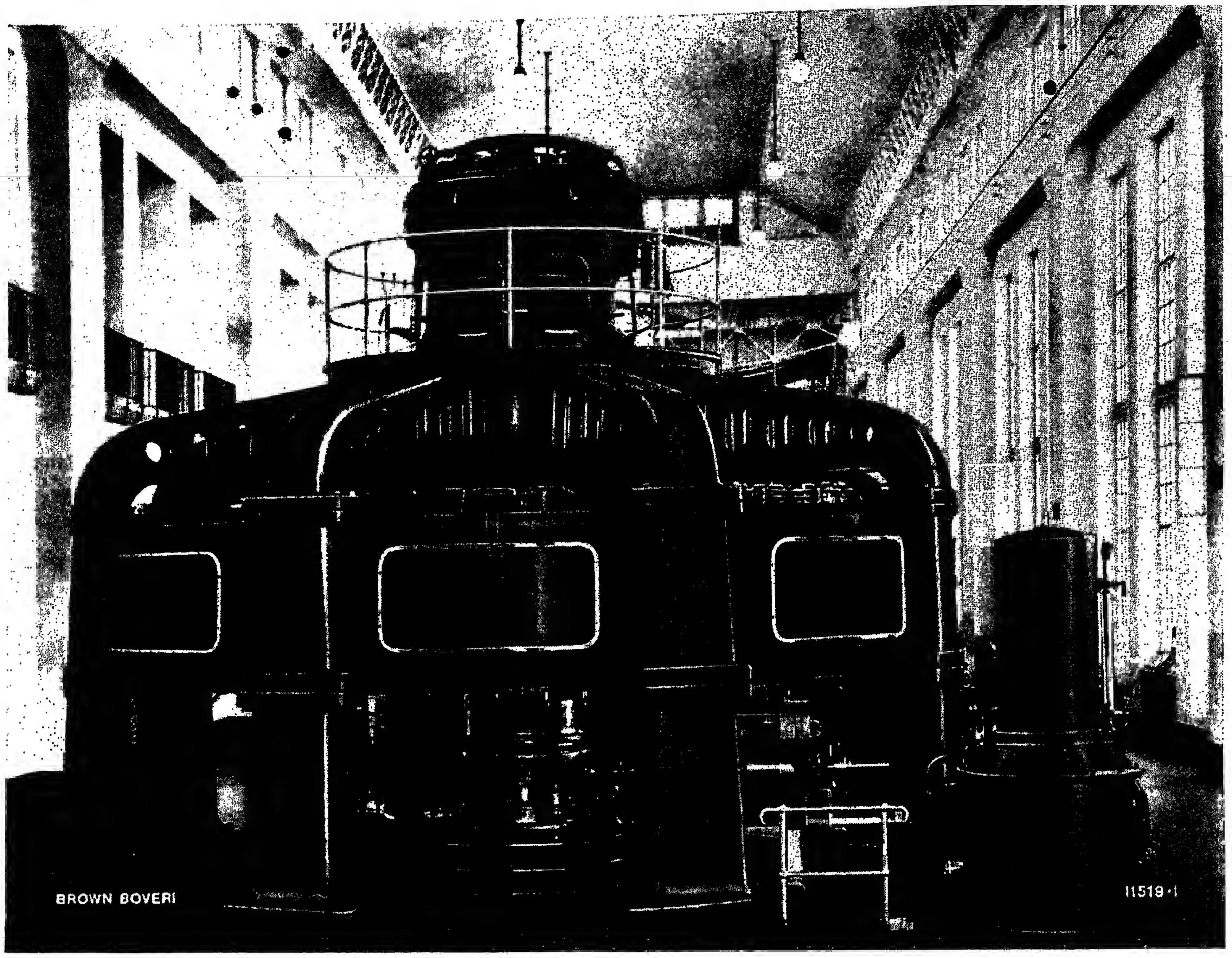


Fig. 12. Alternator at the Goesgen Power Station of the Olten-Aarburg Supply Company.
Seven alternators each for 7050 kVA, 8400 V, 50 cycles, 83·3 r. p. m., have been delivered.

unpleasant for the attendants during summer, the noise is excessive, etc.

The enclosed type of alternator is, therefore, becoming more and more widely employed; here the air is drawn directly from the open and then returned to the open air, or under certain circumstances, used for heating the switch room. The air is drawn in and expelled through canals in the machine room foundations. With vertical-shaft installations, these canals on the lower floor are used as a means of approaching the turbines. With these cooling arrangements the alternator frame is a uniform shape and is secured to the floor of the machine room in a way which makes the joint absolutely air-tight. As the cool air must be led to both ends of the rotor of machines with long cores, many special arrangements have been developed for vertical-shaft machines, in order to supply the upper end of the rotor. Figs. 13—19 show certain examples of this. Another arrangement, as used in the Rempen Power Station of the Wäggital Co., is shown in Fig. 16. Here the alternators are mounted against the wall of the building so that the air may be admitted directly on both sides of the rotor.

If the air supply is not free from dust, it is advisable to install an air filter in the entrance channel. Should the air of the locality be too damp or contain acid fumes, the closed circuit system of cooling, which has proved successful with turbo-alternators, should be used. In this system the same volume of air always circulates in closed channels (Fig. 17). The heat is removed from the air by means of a cooler.

Another question closely connected with ventilation is that of protecting the alternators if the windings catch fire. With protected alternators, either solid or liquid extinguishers had to be used, and frequently more damage was done by the extinguisher than by the fire itself. With closed genera-

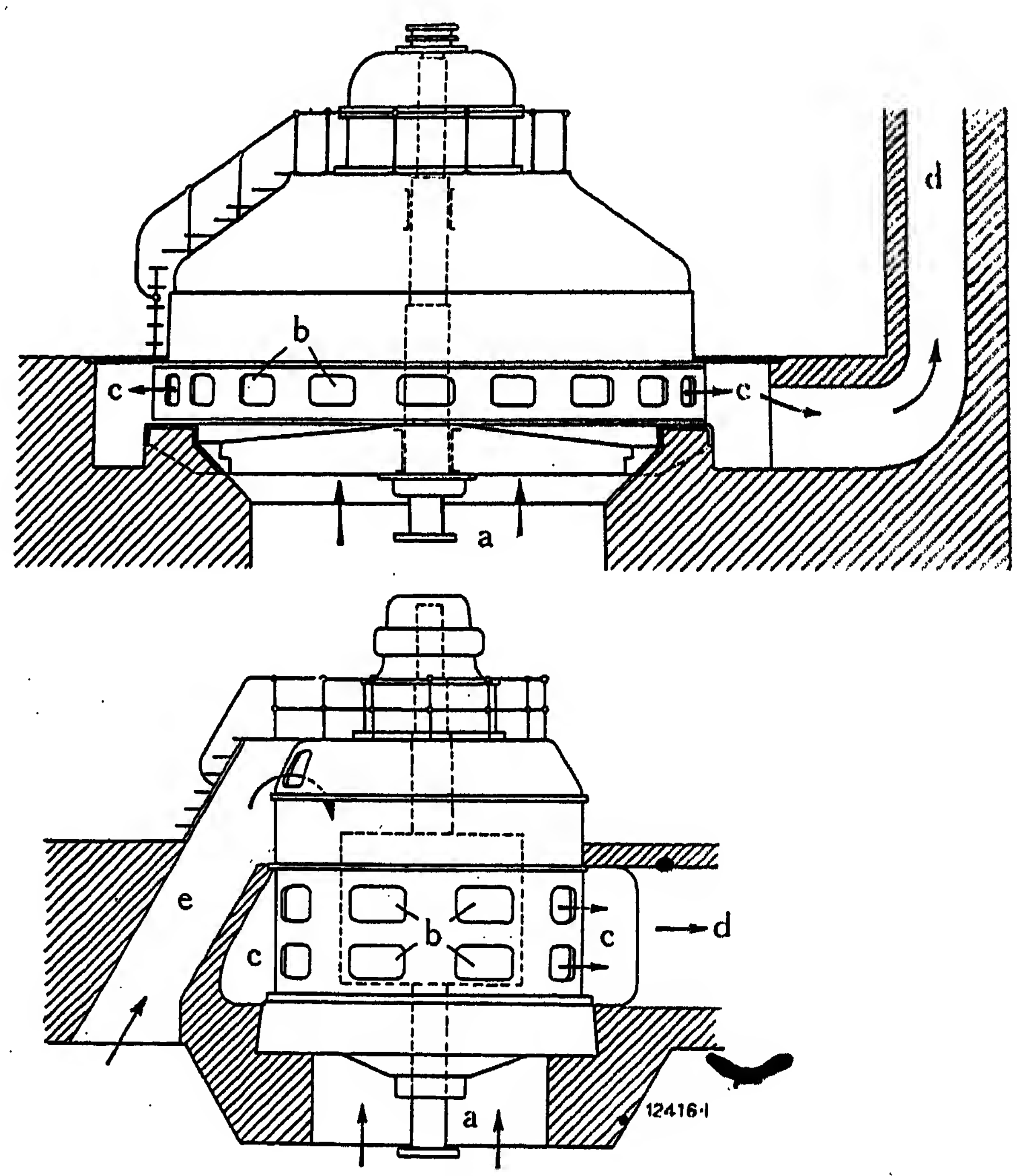


Fig. 13. Air channels for a vertical-shaft alternator.
Above:— For slow-speed machines of small axial length.
Below:— For high-speed machines of large axial length.

tors, an excellent means of combatting outbreaks of fire are provided by introducing an inert gas into the interior of the alternator frame.

In the event of a fire occurring, the air channels are closed, thus preventing a continued supply of oxygen, and in the closed space produced a supply of a gas such as carbonic acid or nitrogen is allowed to escape. It is not necessary to brake the machine; on the contrary, the CO_2 and air mixture necessary for extinguishing the outbreak is produced more rapidly with a rotating machine; the by-passes, if correctly constructed, open automatically. To enable this kind of fire extinguishing to be used every unit must be provided with its own cooling channels; this is advisable for other reasons also, and in new installations it will usually be the case. The fire extinguisher may be operated by hand or by a falling weight which is released by a maximum thermometer, thermo-relay, or better still a differential relay. An essential part of the extinguisher is the valve, which is patented and allows the cylinder to discharge very rapidly, without the outlet freezing. The gas pressure is 60 kg/cm^2. A number of owners of power stations, as for example the Swiss Federal Railways and the Wäggital Supply Company have decided to employ extinguishers of this type after exhaustive investigations.

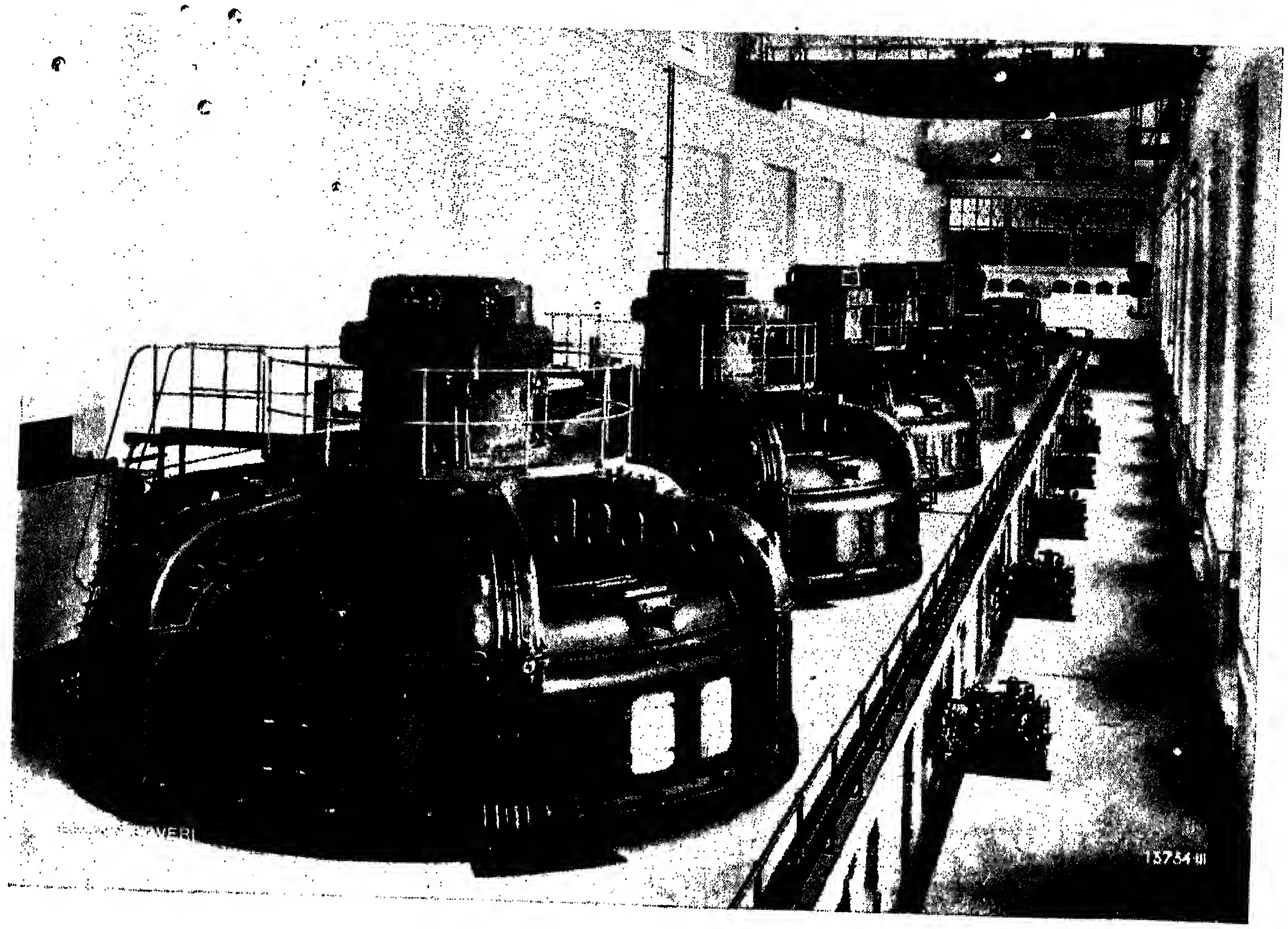


Fig. 14. Mühleberg Power Station of the Bernese Supply Company, Berne.
Six three-phase alternators each of 8000 kVA, 17,600 V, 40 and 50 cycles, 133 and 167 r. p. m.

Fig. 15. Buitreras Power Station of the Soc. Hidro-Electrica del Guadiaro (Spain).
Two of the three three-phase alternators each for 3000 kVA, 5000 V, 50 cycles, 750 r. p. m.

The very large rotating masses often contained in the pole wheel affect the time required for the set to come to rest after the turbine has been shut down; this time frequently exceeds half an hour. In order to save the heavily loaded thrust bearing of vertical-shaft sets, the alternators are generally fitted with a pneumatic braking device, i.e., a cast iron rim is mounted on the rotor, and on to this the

Brake blocks are applied by means of compressed air. A Brown Boveri motor compressor, with a few accessories, is suitable for furnishing the compressed air necessary for a power station. If the compressor is of the portable type, it can be used for removing the dust from the alternators and switchgear (Fig. 44). On account of the metallic dust which always occurs when the brake is applied and which can penetrate into the windings, it is not advisable to use the brake until the speed has fallen to a half of its full value; or, the brake disc may be mounted near the turbine away from the air channel. A braking turbine or, with Pelton wheels, a braking nozzle, can also be provided.

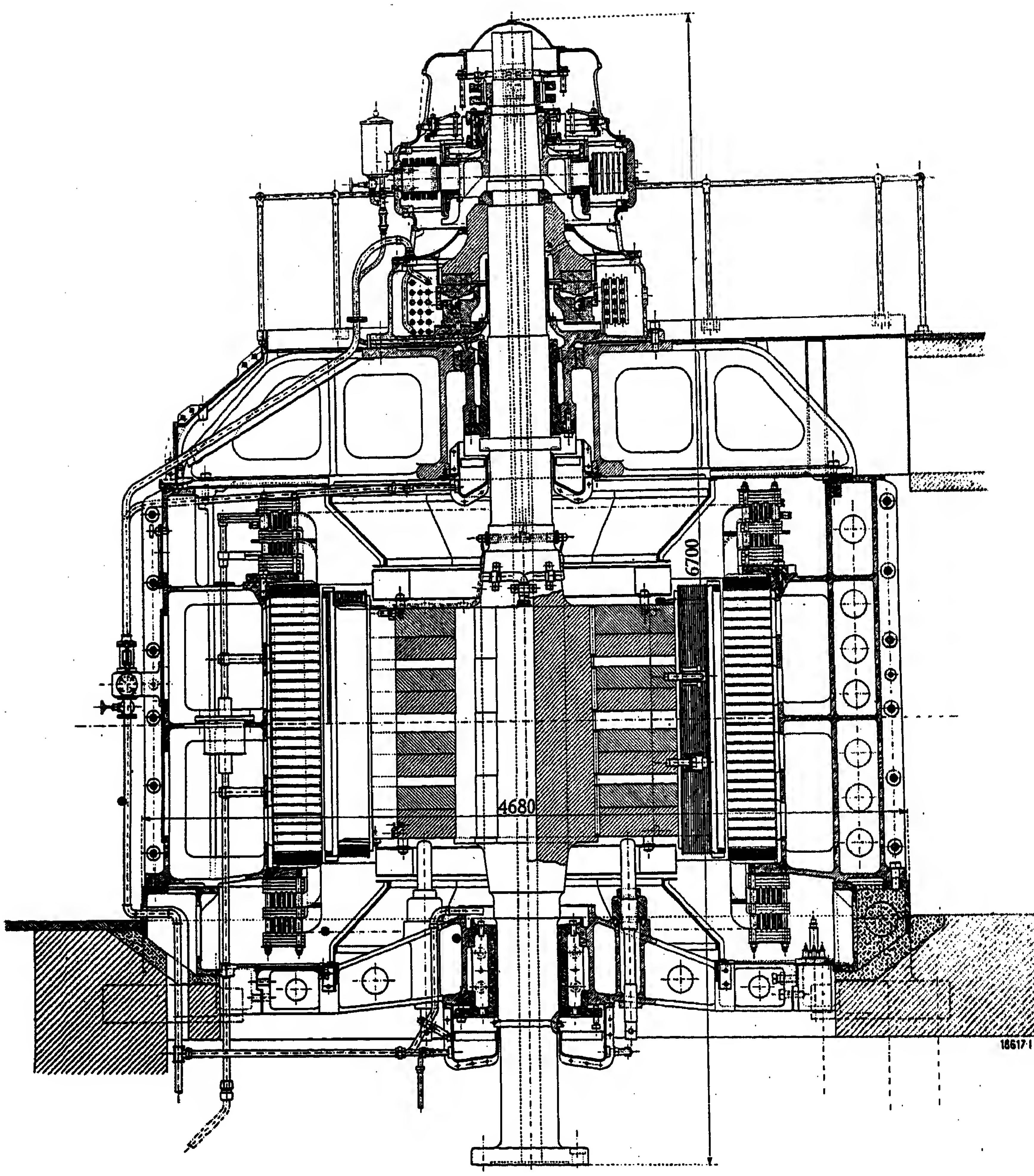


Fig. 16.
Section through a three-phase alternator for 16,500 kVA, 8800 V, 50 cycles, 0·8 power factor, 500 r. p. m.

Four machines of this type have been supplied for the Rempen Power Station of the Wäggital Supply Company.

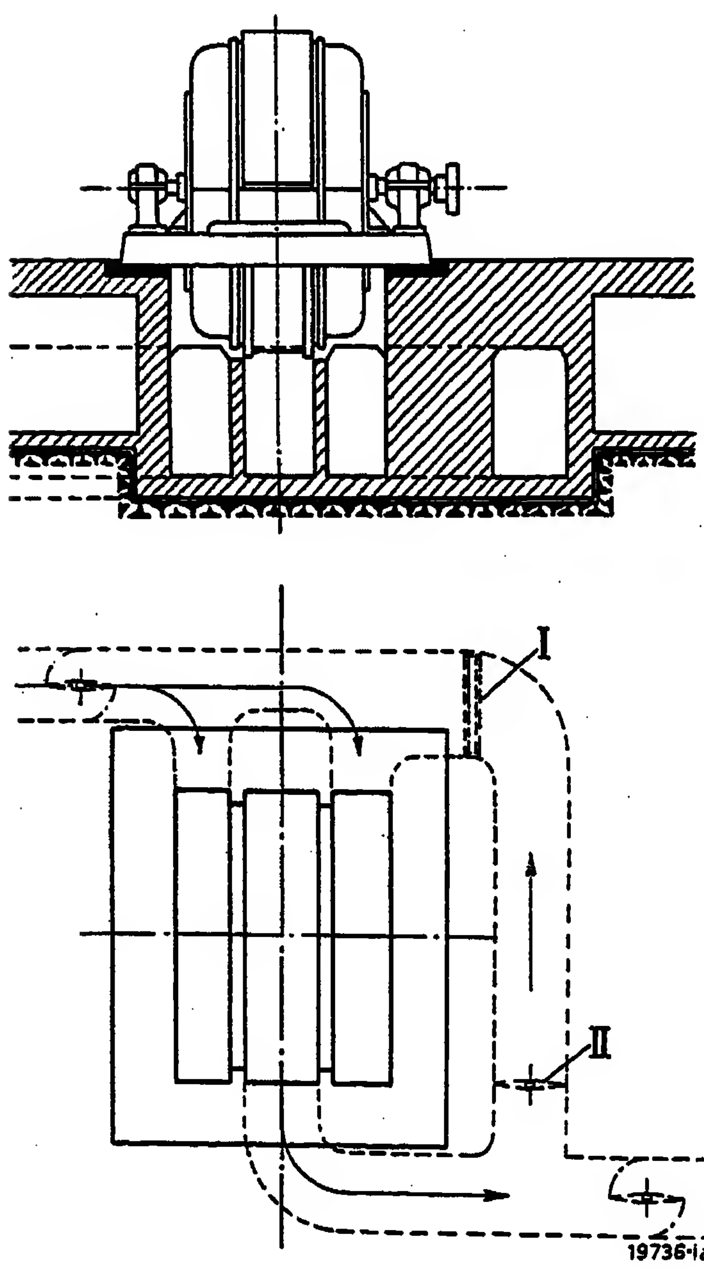


Fig. 17.
Diagram of closed-circuit cooling (left).

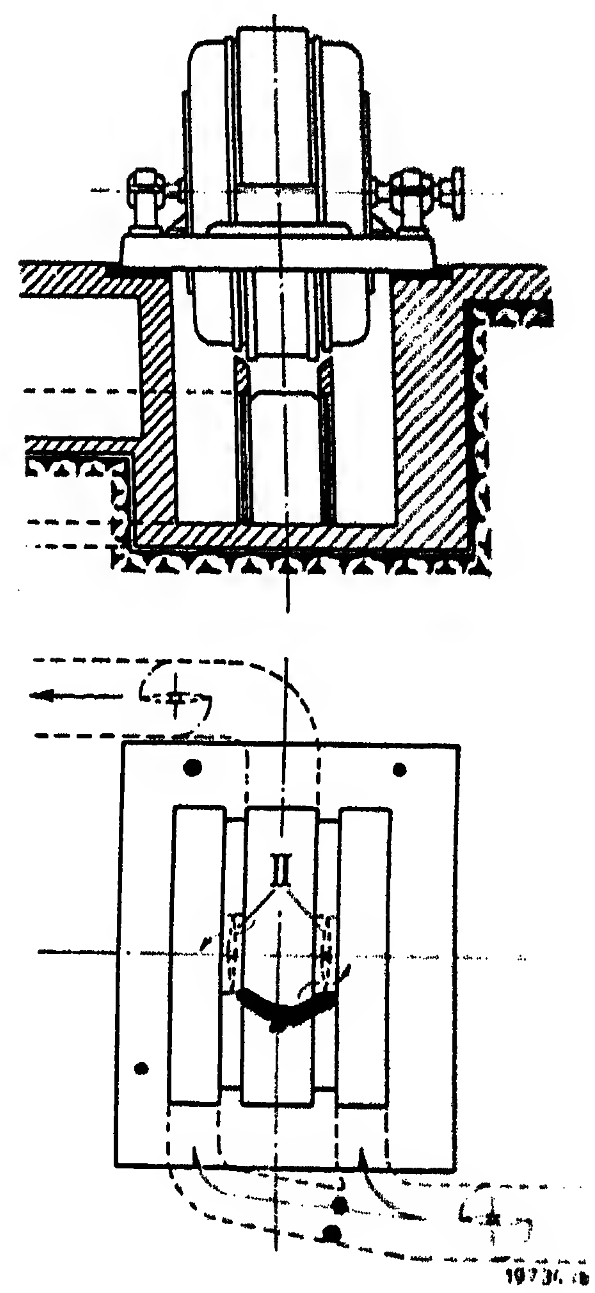
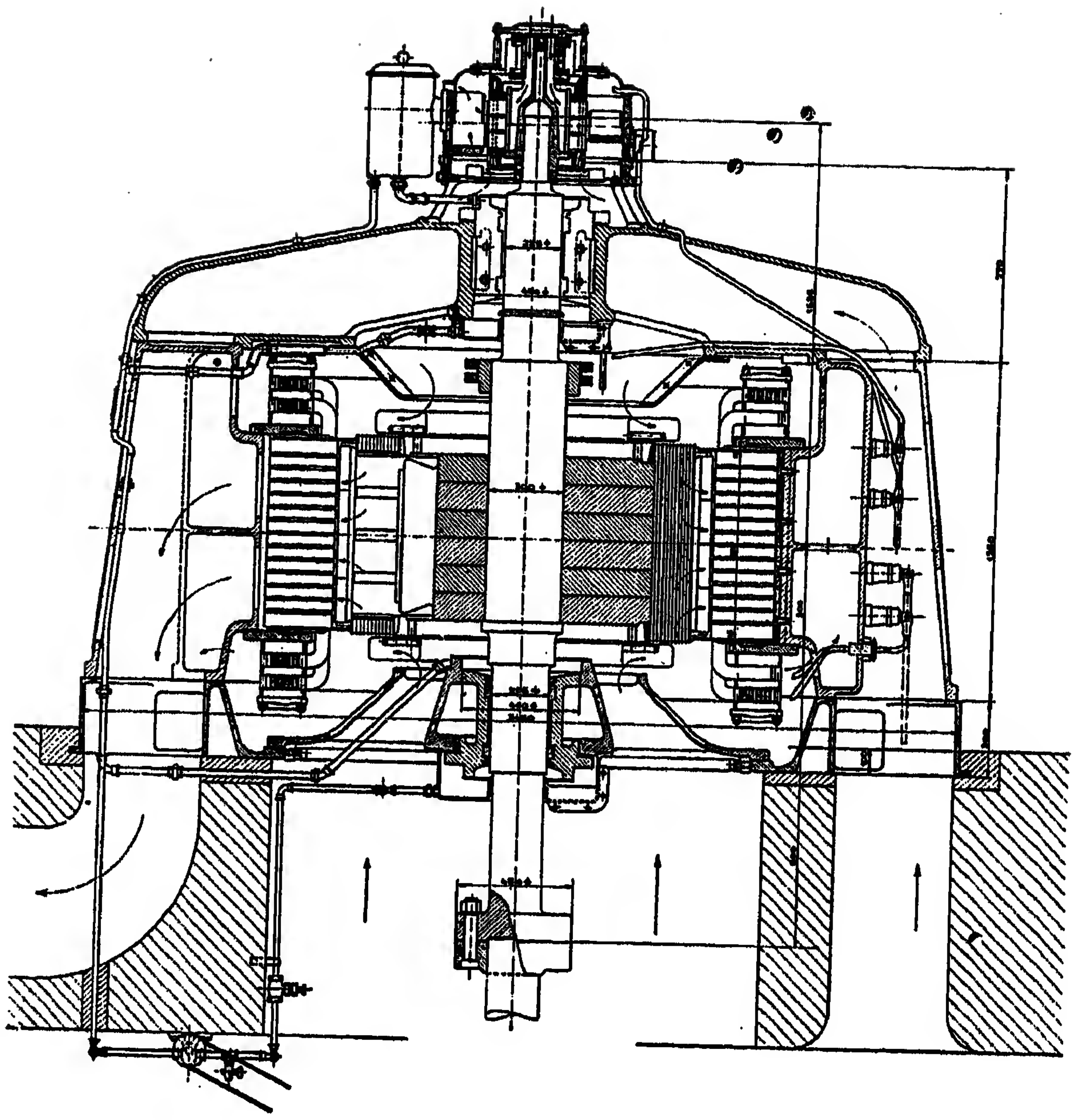


Fig. 18.
Pipe ventilation with closed-circuit cooler for protection from fire (right).
I. Air cooler. II. Circulation control valves.

Brown Boveri alternators are fitted with various constructive details which simplify in a large measure the work of erection and inspection. A detailed description of Brown Boveri alternators for coupling to water turbines is given in brochure 854 E, "Alternators for hydro-electric power stations".



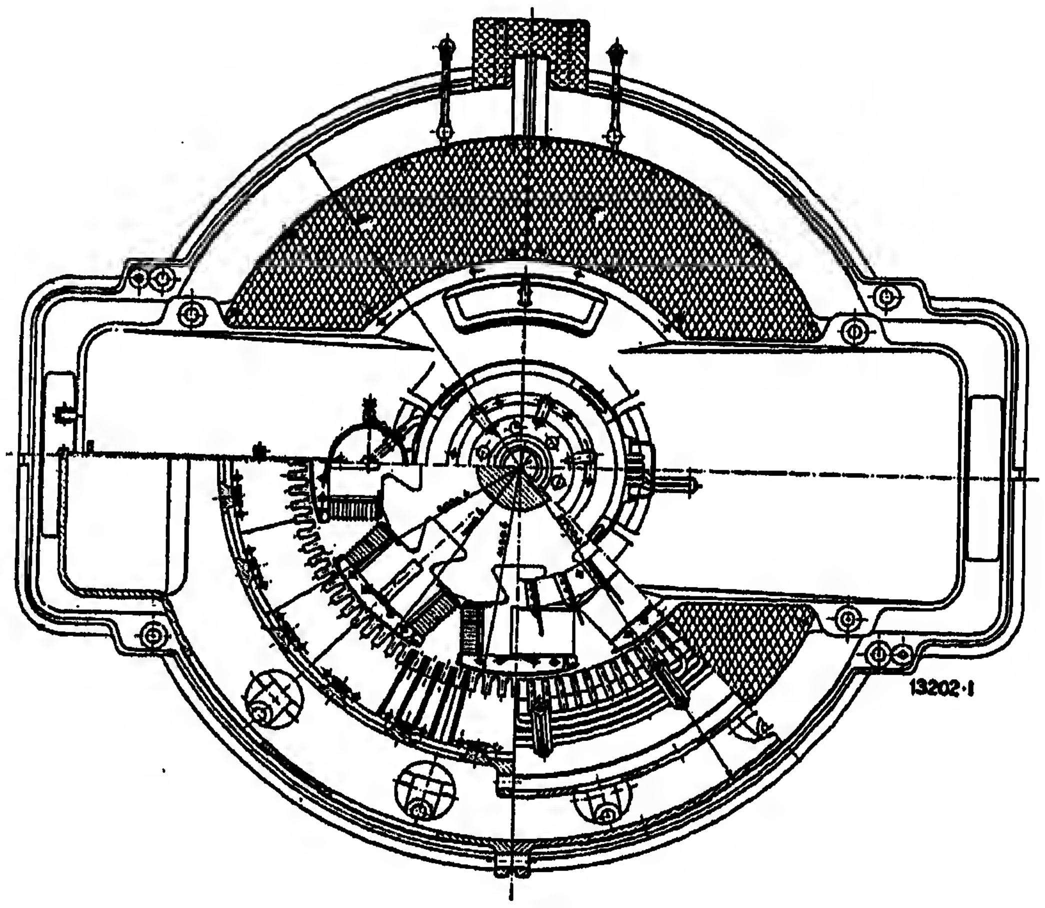


Fig. 19. Section through a vertical-shaft three-phase alternator installed in the Buitrereas Power Station.

4. EXCITATION.

The general principle in modern power station construction is the division of the installation into a number of self-contained units. A unit consists of an alternator, turbine, hydraulic and electric accessories, and the auxiliary plant. Undoubtedly the most important of the auxiliary equipment is that connected with the excitation. Individual excitation machines, as now used, bring with them great advantages when compared with the centralised excitation plant, which was formerly usual. If an exciter breaks down, the interruption in service is limited to a single alternator, but, with central excitation, a failure causes the complete station to be shut down. On this account, in stations with central excitation, at least one, but generally two, spare exciter sets are installed. As the danger of an interruption to the whole excitation system does not exist when individual exciters are used, therefore, it is not so vitally important to maintain a reserve plant for this purpose. If, however, it is decided to install a spare exciter the cost is considerably less, as the stand-by set only requires an output sufficient for the excitation of one machine. The probability of the exciter failing is, however, so slight that a reserve armature and the usual spare parts for the exciter usually suffice. An important saving on the initial cost is thus obtained, and this is still more obvious if the great advantages of individual excitation are considered. Main resistances in the excitation circuit of all the alternators are necessary with central excitation. This apparatus is expensive, requires floor space, and moreover has the great disadvantage that energy is continually consumed. Special considerations are required when installing these resistances in order that the heat generated may be suitably dispersed; this arrangement also necessitates the use of long cables and complicated control devices. The quantity of direct current energy to be distributed from the central excitation plant, by way of the main resistance, to the alternators is often considerable and requires a complete system of excitation bus-bars and distribution leads. If individual excitation is used, all of these complications are avoided. By a special construction of the poles of the exciters, their pressure can be regulated, in a perfectly stable manner, within wide limits by a simple shunt resistance. The main resistances are thus entirely superfluous for the usual conditions. The complicated, long,

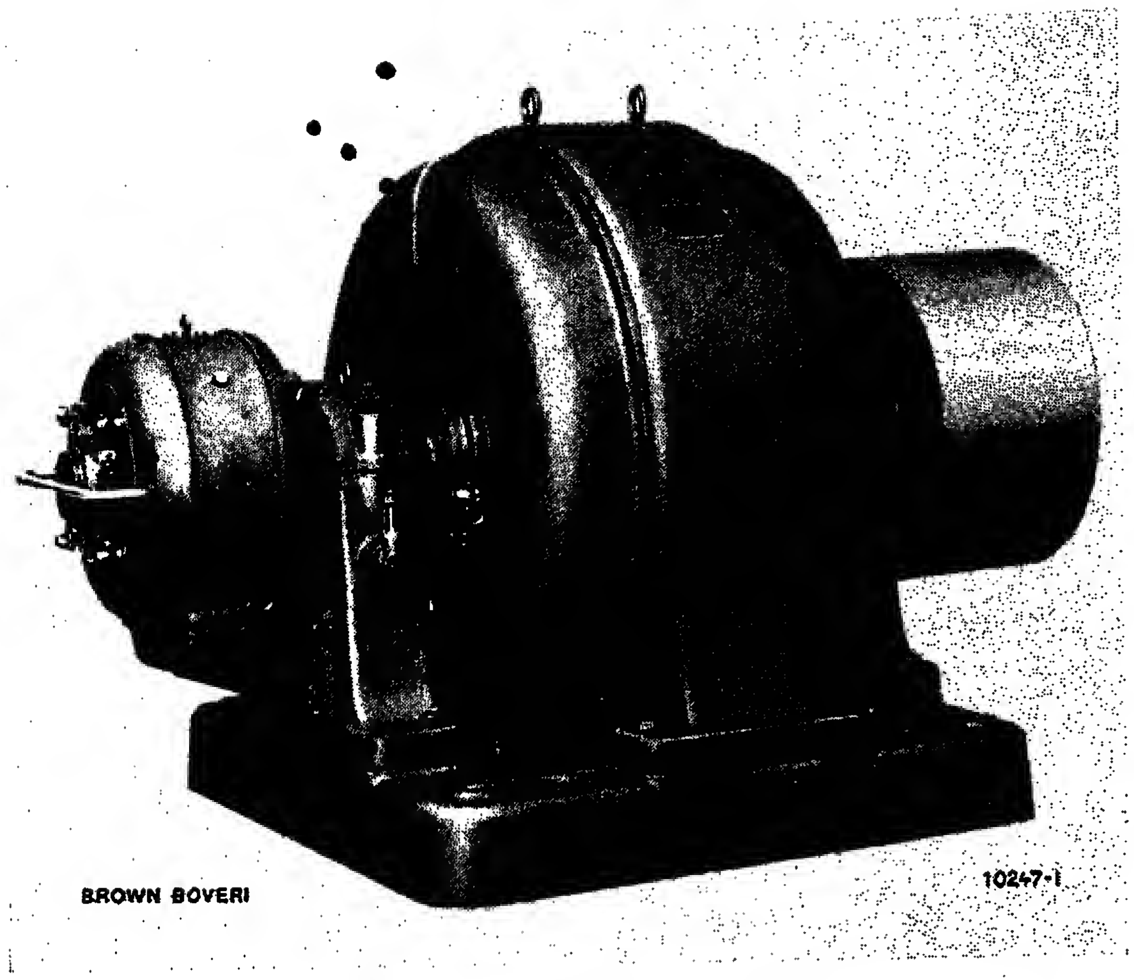


Fig. 20. Generator with built-on exciter.

main current leads, etc., can also be omitted. Only two short connections between the terminals of the exciter and the corresponding alternator, and two shunt leads, of small cross section, from the exciter to the switchboard, where the shunt regulating resistance can be mounted owing to its small size and light weight, are necessary. This is a great simplification if automatic regulation is required. The Brown Boveri quick-acting regulator which is specially designed for this work, has been used for some years in all the larger stations in Switzerland, and in numerous power houses in other countries, with excellent results. It is preferable to install a quick-acting regulator for each alternator, i.e., for each exciter. Besides effecting the pressure regulation automatically, these regulators also ensure the uniform distribution of the wattless current between all paralleled alternators. Full particulars of the Brown Boveri quick-acting regulator are contained in Brochure 786 E. Fig. 23 shows the diagram of connections of a power station equipped with individual excitation and automatic pressure regulation.

The saving of floor space in the machine room, and the simplification of the foundations by the

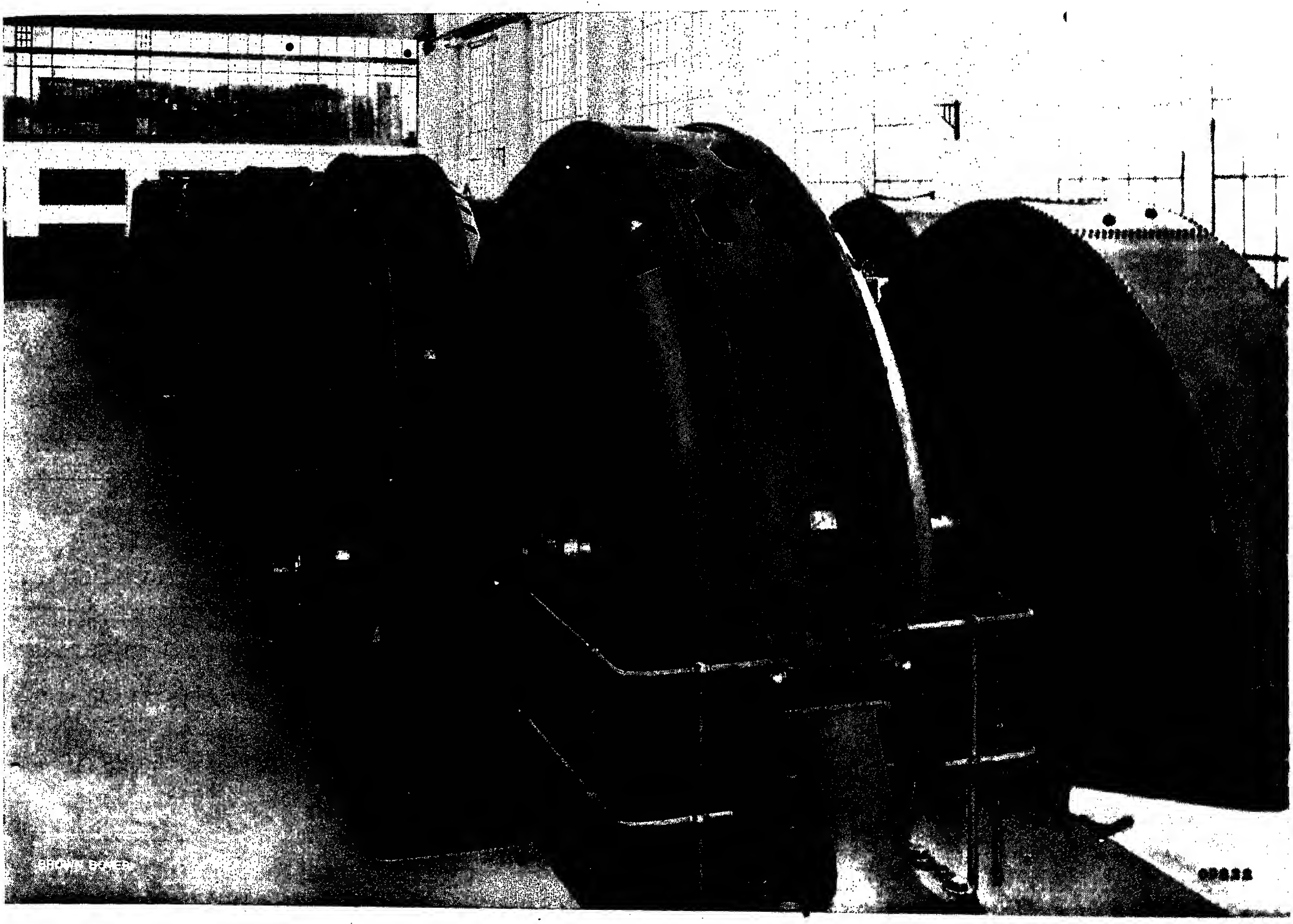


Fig. 21. Example of a power station equipped with alternators with individual excitation.

omission of the driving machines required for central excitation, are advantages of individual excitation which must not be overlooked.

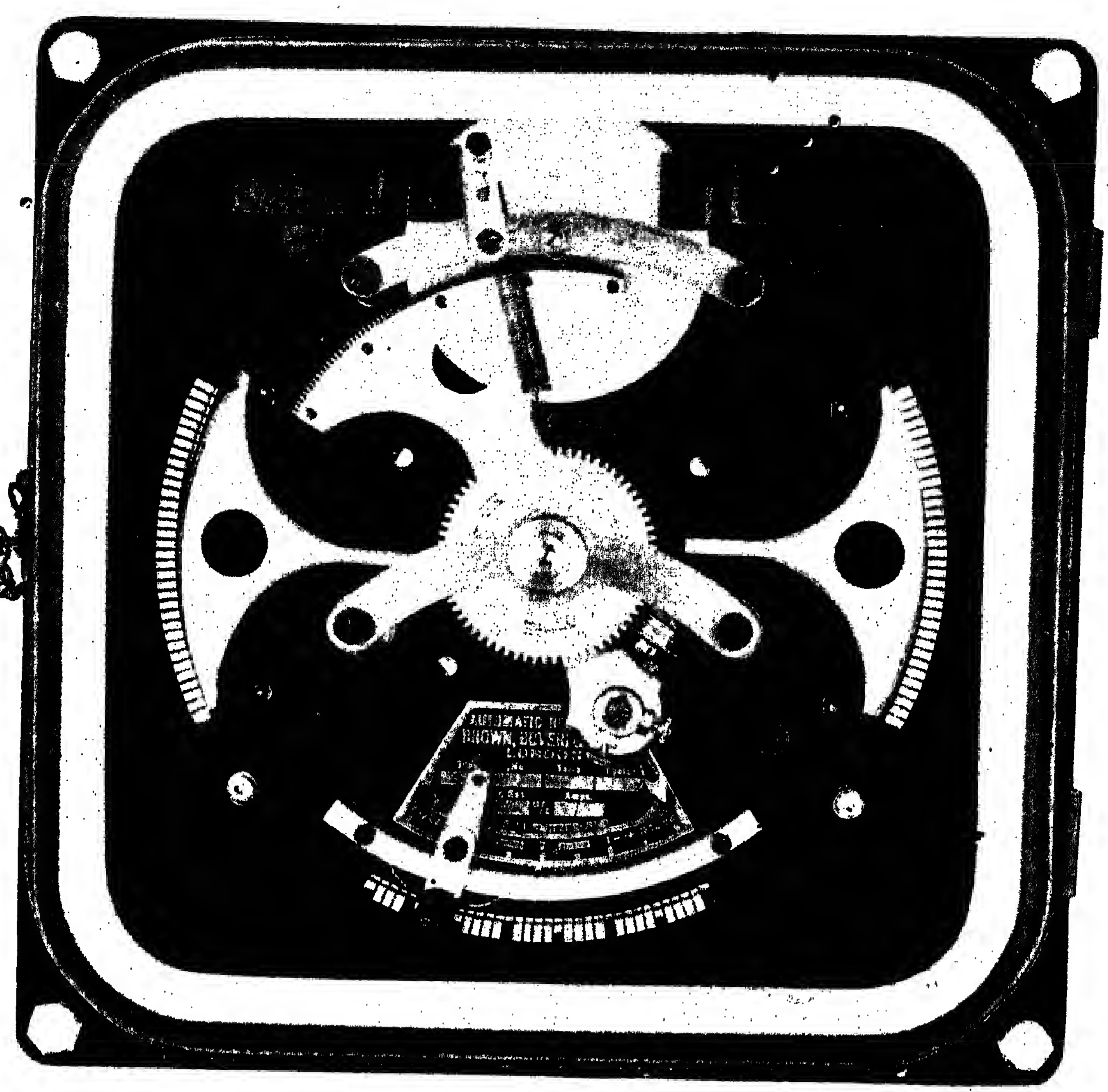


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Fig. 22. Brown Boveri quick-acting regulator.

The simplest method of driving the individual exciter is to increase the length of the alternator shaft and mount the armature of the exciter directly on it; the stator frame is fixed to a bracket which is rigidly connected with the bearing of the alternator. Exciters are not built on to very slow-running alternators, but it is advantageous to drive them from the alternator or governer shaft by means of belts or gears. It then becomes possible to use high-speed direct-current machines for the excitation, thus obtaining a considerable saving in cost. The same method may be used for horizontal-shaft alternators if no shaft-end, to which the exciter may be coupled, is free. This can arise with hydro-electric sets which are provided with two turbines, either for use with different heads or for reversible sets. Low-head stations sometimes employ a plant of this kind for using the power during the night; the alternator runs as a motor and drives a centrifugal pump which lifts the water to a high-level reservoir. With power stations which work in parallel with other stations, or which have sufficiently large storage batteries, the excitation current may be obtained from a small motor-generator set, the driving motor being supplied from the alternating-current mains. The alternator and its exciter are mechanically divided, but they can be regarded as an electrical unit.

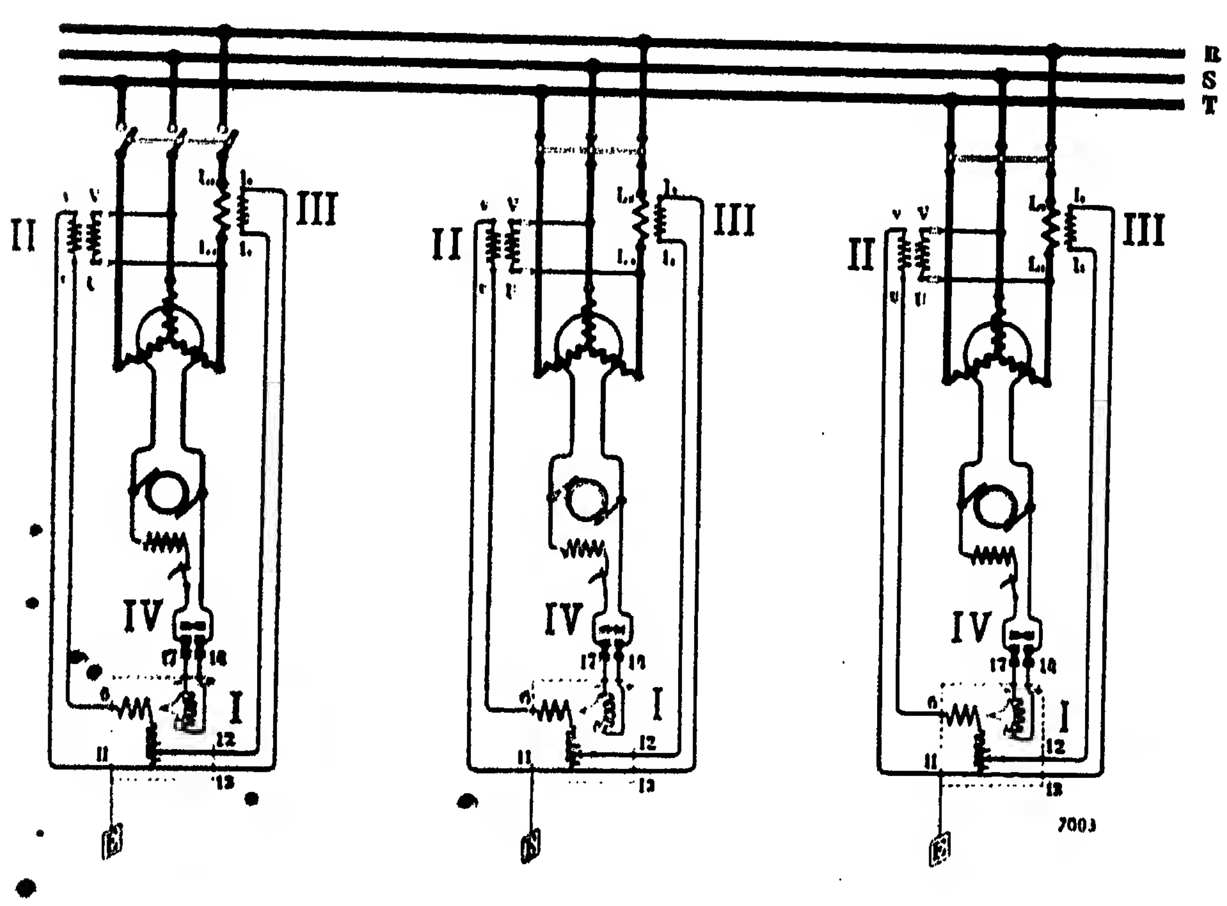


Fig. 23. Diagram of connections for a power station with pressure regulation by means of Brown Boveri quick-acting regulators.

I. Quick-acting regulator.
II. Potential transformer.
III. Current transformer.
IV. Exciter change-over switch.

Although the advantages of individual excitation over central excitation, as explained above, are decisive, attention may still be drawn to another point. An excess current regulator for each alternator may be used with individual excitation, as well as the automatic pressure regulator (Fig. 22). This apparatus, patented by Brown, Boveri & Co., immediately reduces the excitation of all alternators affected if a short circuit takes place. By this means the short-circuit current is considerably reduced and the thermal and dynamic effects greatly diminished. The tripping of the switch due to short circuits which only last for a short time can be completely avoided, while, with persistent short circuits, the switch is, to a great degree, saved by the reduction of the E.M.F., and consequently, of the energy to be

interrupted. (See Revue BBC, 1921, No. 8 and Brochure 728 E, "The Brown Boveri system of automatic current-limiting regulation".)

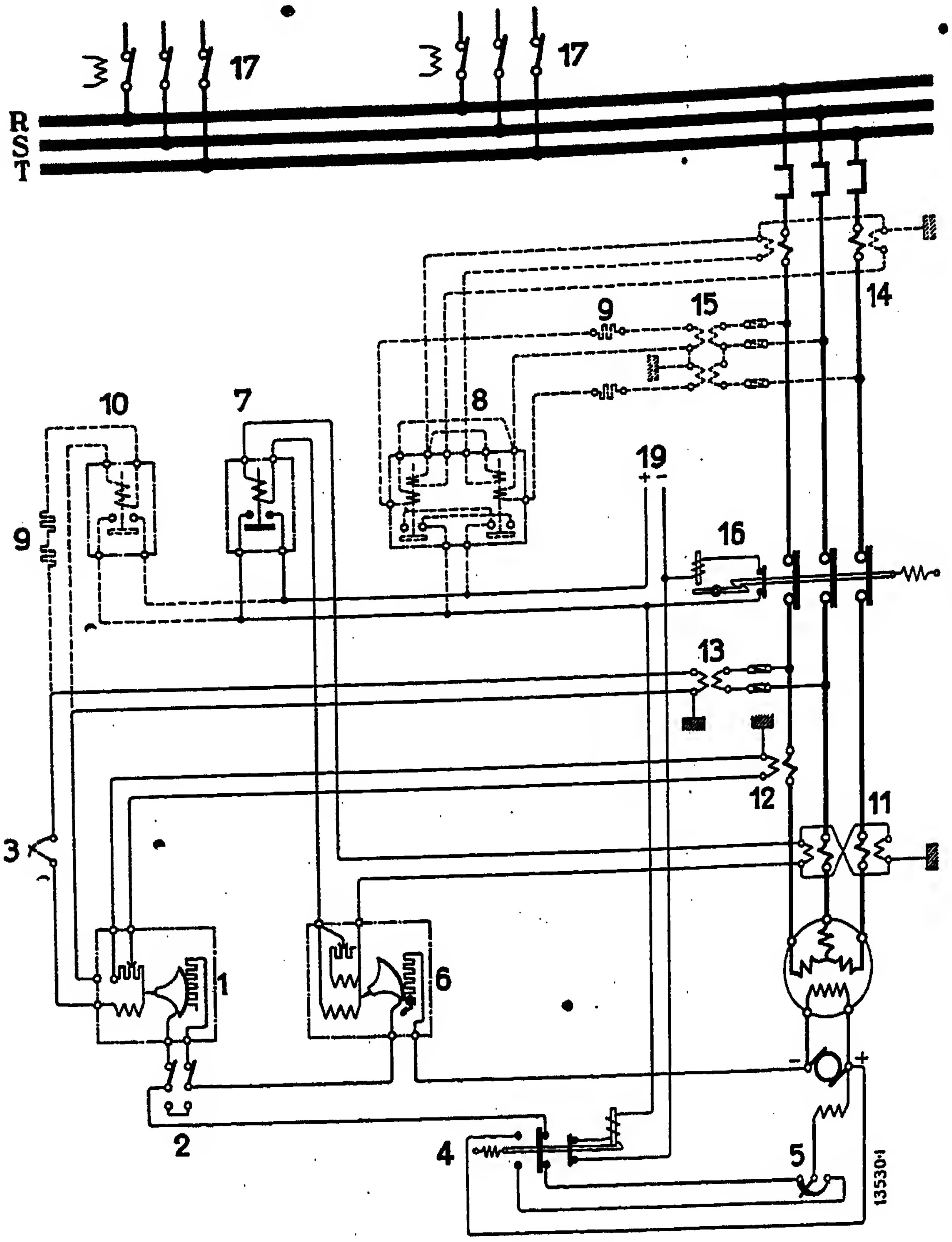


Fig. 24. Diagram of connections for an alternator panel with overload protection by means of Brown Boveri current limiting regulators.

1. Pressure regulator. 2. Change-over switch. 3. Adjustable resistance. 4. Field switch with tripping magnet. 5. Field regulator. 6. Current limiting regulator. 7. Maximum current relay. 8. Reverse power relay. 9. Resistance. 10. Maximum pressure relay. 11. Current transformer. 12. Current transformer. 13. Potential transformer. 14. Current Transformer. 15. Potential transformer. 16. Alternator switch. 17. Feeder switch. 19. Auxiliary current supply.

The only disadvantage which arises with individual excitation of the alternators is that, should a turbine run-away, the electric pressure may increase to a value which is dangerous to the insulation. This danger can be overcome in a simple manner; although the automatic pressure regulator counteracts the increase of pressure, the alternator is also provided with a maximum pressure relay, which trips the field change-over switch when a certain pressure is exceeded. The field winding of the exciter is thus switched out, and short-circuited by a resistance; hence the alternator is rapidly demagnetised. Since, as previously mentioned, the rotors of Brown Boveri alternators are made safe against the action of centrifugal forces, they are, therefore, able to withstand the greatest mechanical forces that can occur, without danger of the pole wheel bursting.

5. TRANSFORMERS.

Apart from a few cases, as, for example, if most of the energy is supplied to an electro-chemical works near the power station, the energy generated must be transformed to the pressure which special tests have proved to be the most suitable for transmission. Here, too, when designing and drawing up the diagram of connections, the unit output of the transformers must be decided upon, the probable working conditions being taken into account. This output must be always at least equal to the output of one of the alternators; it is usually most suitable to make the transformer output equal to the alternator output. If this is so, various simplifications can be introduced which result in a considerable cheapening of the switchgear. Every alternator is connected to a transformer so that the two form an independent unit, as previously mentioned. If such an arrangement is decided upon, only one switch panel, or a single oil-switch, is necessary for each alternator-transformer set. The low-tension bus-bars may be omitted, and instead auxiliary bus-bars be fitted; these supply the current for the transformers dealing with the station requirements, and, by means of isolating switches, enable any transformer to be connected with any of the generators. This possibility is of special value during inspection or repairs. Suitable means of interlocking must be fitted, especially with large units, to prevent alternators being paralleled on to the auxiliary bus-bars. Its hould be possible to connect only one unit at a time to the auxiliary bus-bars.

In Europe, three-phase transformers only, are used with three-phase power, while in America single-phase transformers, delta connected, are employed in many places. This solution may be applied

where bad transport conditions exist, as, by this means, the individual weight is considerably reduced. It must be mentioned, though, that in the event of one of the transformers being damaged, the service may be maintained with the other two to the extent of 67% normal output, provided that the transformers are connected in delta-delta, which is seldom the case. If, however a single-phase transformer is provided as a reserve the delta-star connection can be adopted. The financial drawbacks with this method are very great, and, it should only be used under pressure of very special conditions. As the cost of a single-phase transformer is about a half of that of a three-phase transformer with three times the output, the use of four single-

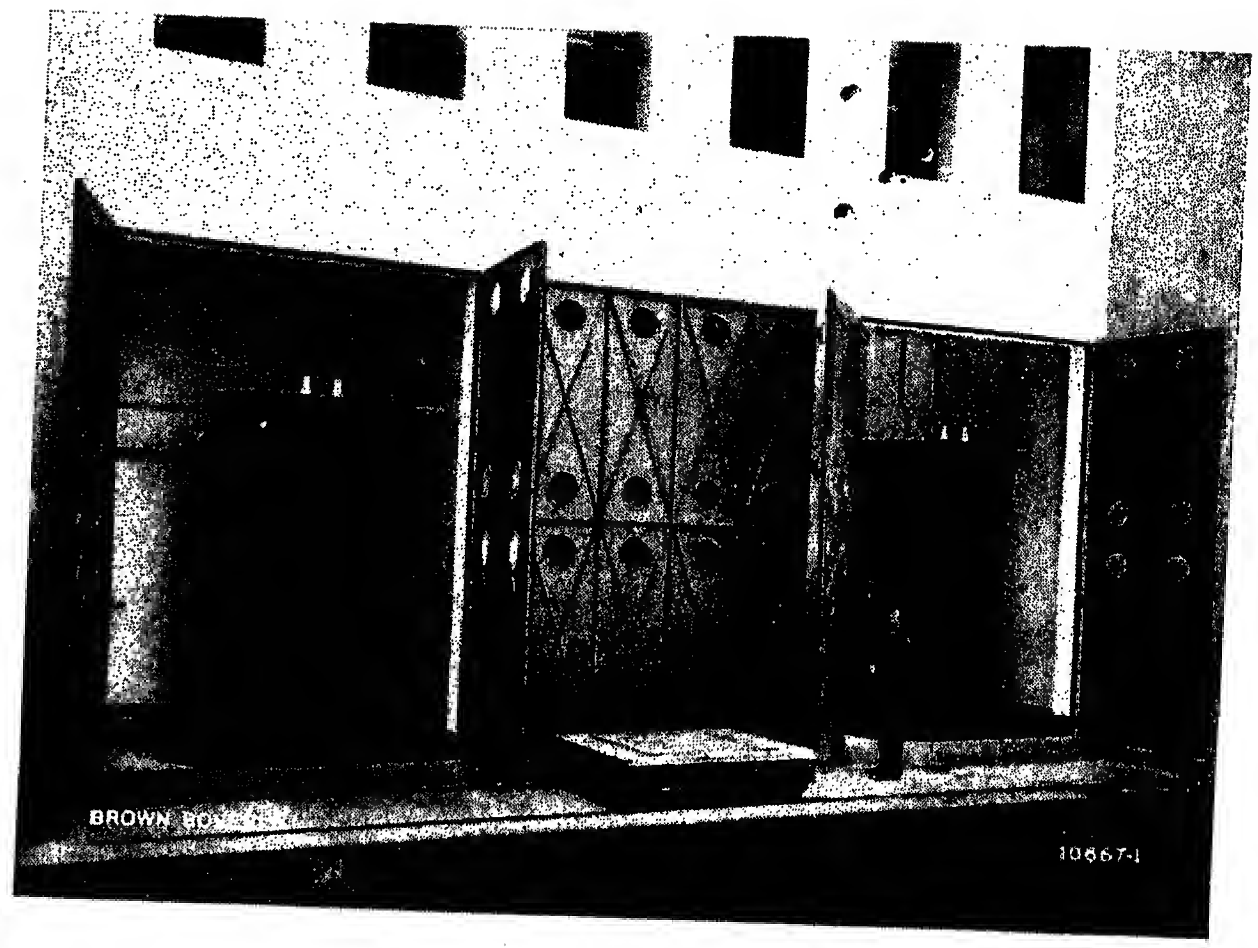


Fig. 25. Transformers installed in cells.

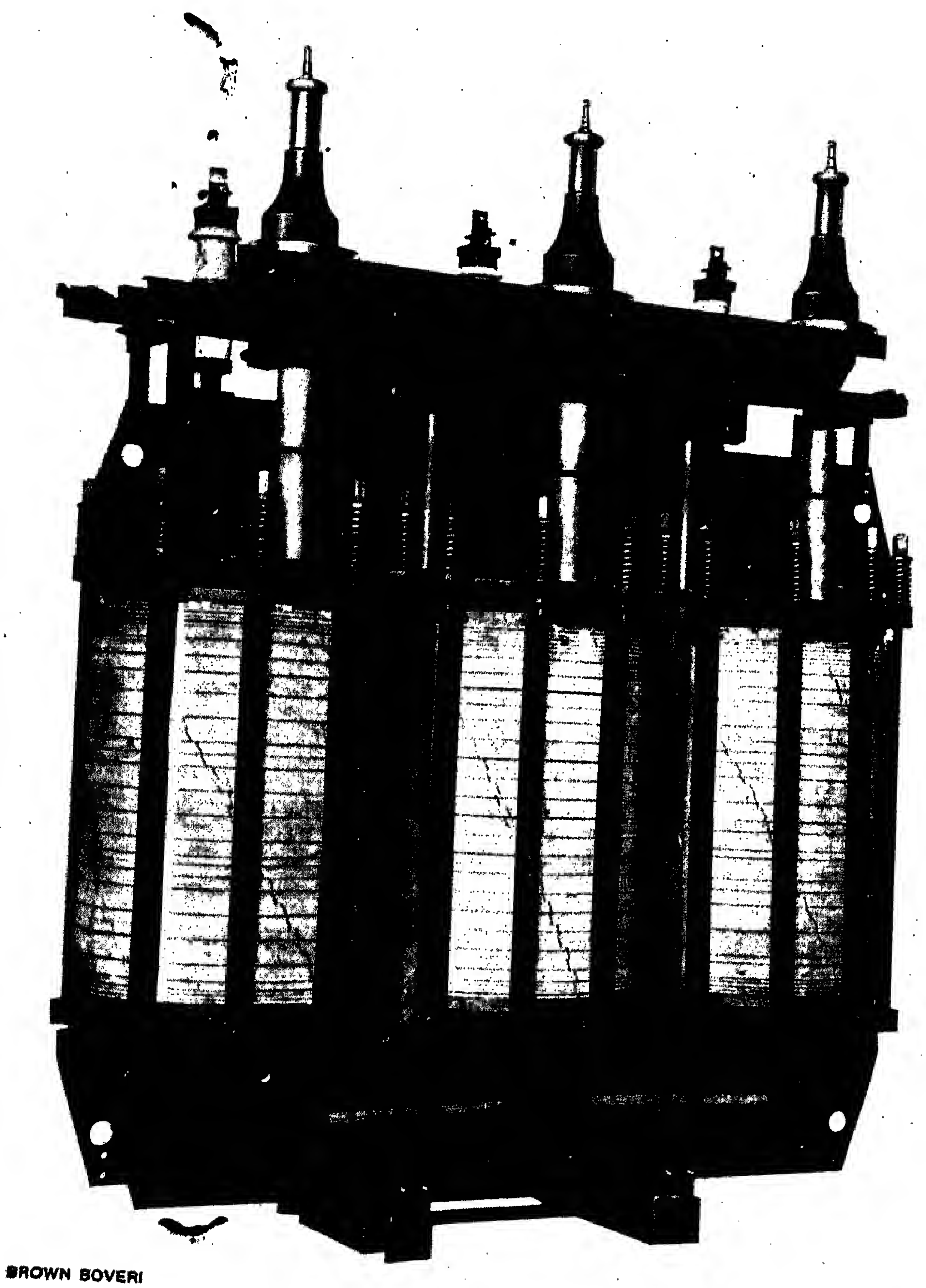


Fig. 26. Three-phase transformer with external cooling; 2000 kVA, 3000/25,000 V, 16⅔ cycles.

phase transformers (of which one acts as a stand-by) is as expensive as that of two three-phase transformers of which one is in reserve. With an increasing number of transformers and a constant reserve (in each case only one unit) the difference in price is more and more in favour of the use of three-phase transformers. The space required when single-phase transformers are used is greater; hence the building costs are unfavourably influenced with this method. In addition to this, the system of conductors is very complicated, the cooling apparatus is triplicated, the supervision is difficult, and the possibility of failure increased. Finally, the iron losses of a bank of three single-phase transformers are considerably greater than those of the corresponding three-phase transformer, so that the lack of economy with this method is even more clearly shown if the increased consumption is capitalised.

For the outputs necessary in modern power stations, only oil-cooled transformers can be utilized for stepping up the pressure. In hydraulic stations where there is plenty of water,

it is advantageous to use water for cooling the transformer oil, as a capital saving on the plant is thereby effected. For outdoor transformer stations, transformers in which the oil is naturally cooled, are often preferred on account of the decreased attendance involved. The tanks of transformers for large outputs must be provided with suitable cooling radiators, as shown in Fig. 27. Formerly the oil was invariably cooled by water under pressure which circulated through nests of tubes built into the transformers. For large outputs it has been found advantageous to replace this method of internal water cooling by an external cooling system in which a pump draws the oil from the top of the transformer, circulates it through a cooler and finally delivers it at the bottom of the transformer tank. The coolers are arranged on the counter-flow principle, i.e., the water flows through straight tubes, baffles forcing the oil to circulate round them. External circulation cooling has the advantage that, should a leak appear in the coolers, water cannot enter the oil, as the latter is under a considerably higher pressure than the water. Suitable apparatus is fitted to enable the oil flow to be observed, and to signal a stoppage in the cooling water supply. Special attention is paid to packing the joints of the oil pipes. It is recommended that only pipes with flange connections should be used for the oil circulation.

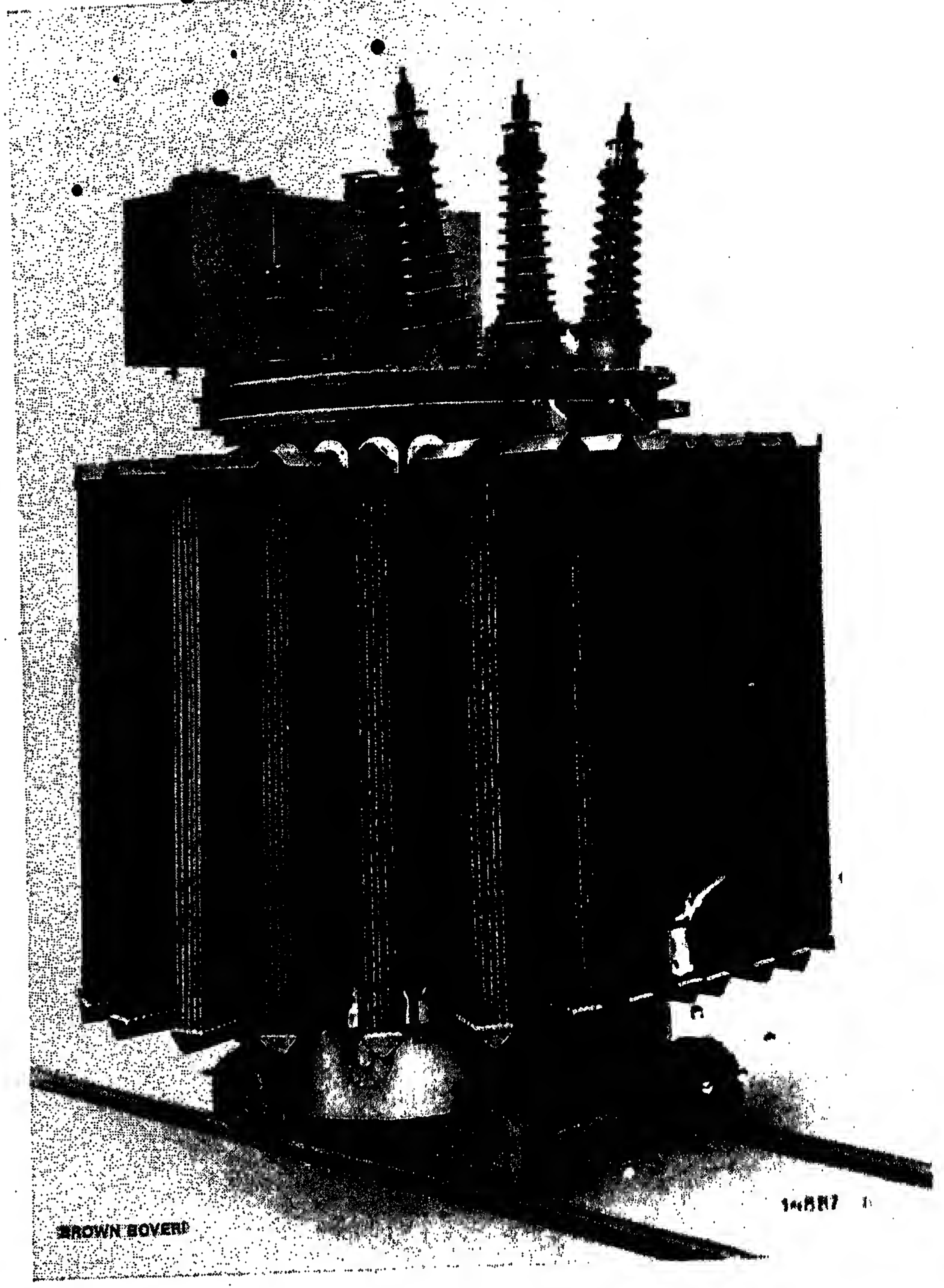


Fig. 27. Transformer with naturally cooled oil for outdoor installation; 5000 kVA, 60/15 kV, 16⅔ cycles, supplied to the Puidoux Substation of the Swiss Federal Railways.

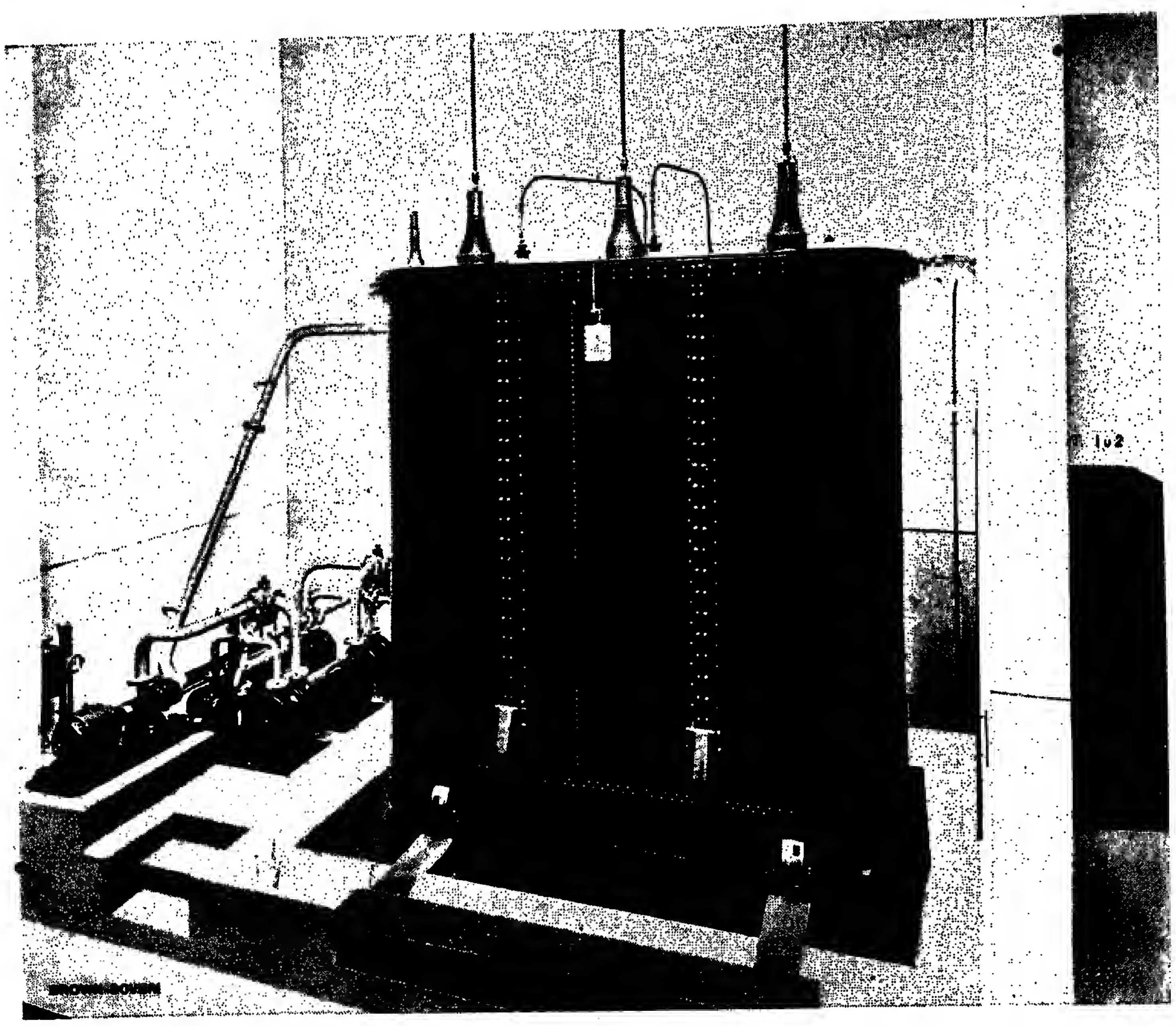


Fig. 28. Transformer with external closed-circuit cooling and cooling apparatus as installed in Goesgen Power Station; 7050 kVA, 8860-8630-8400/77,370 V, 50 cycles.

6. SWITCHGEAR.

The progress in switchgear has been more marked than in any other branch of power station construction. The conditions which have to be met have increased greatly owing to the pressure and outputs being raised and the extensive interconnection of systems. In the older installations the switchgear was usually installed in any odd corner of the machine house. Experience, in the meantime, has shown the deficiencies in the old switchgear, and contributed to the

explanation of many questions; hence, to-day, suitable general rules relating to the construction can be laid down. The most important principles are referred to in this article.

Special care must be paid to the design of the switchgear, which must be as simple as possible; the ability of the switchgear to meet possible future operating conditions must also be considered. The switchgear is correct when these requirements can be fulfilled with the minimum amount of apparatus.

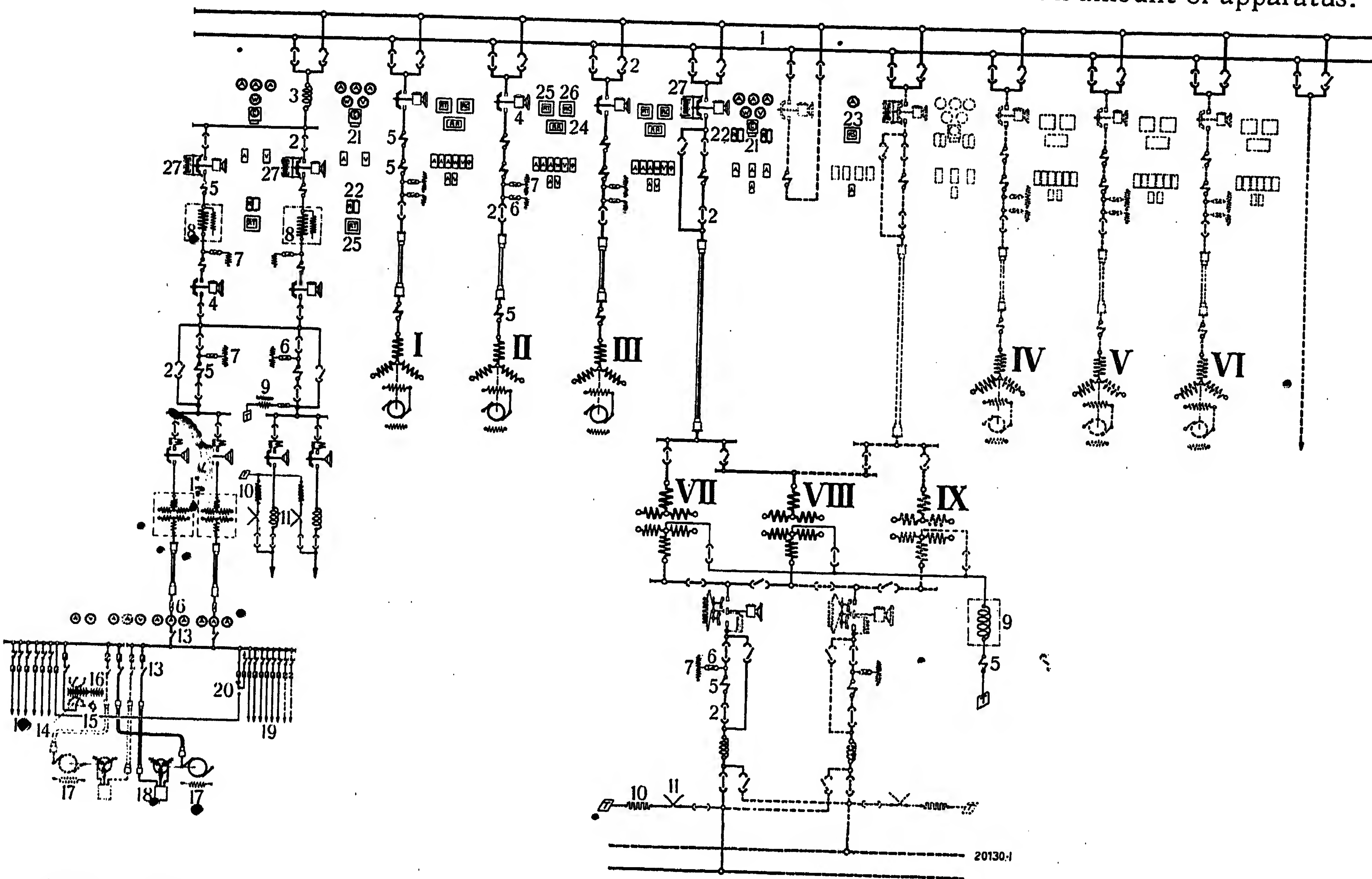


Fig. 29. Diagram of connections of extensions of the Bois Noir Power Station at St. Maurice in the Rhone Valley.

1. Bus-bars 5500 – 65,000 V.
2. Isolating switch.
3. Choke coil.
4. Oil switch with remote control.
5. Current transformer.
6. Fuse.
7. Potential transformer.
8. Induction regulator 5400 – 6600 V, 20 kVA.
9. Earthing choke coil.
10. Water resistance.
11. Horn gap lightning arrester.
12. Station transformer.
13. Lever switch.
14. Double cell switch.
15. Automatic discharge.
16. Battery.
17. Motor-generator set.
18. Starter.
19. Outgoing line.
20. Automatic change-over switch for emergency lighting.
21. Meter.
22. Maximum time-limit relay with independent time adjustment.
23. Automatic synchroniser.
24. Reverse power and excess pressure relay.
25. Pressure regulator.
26. Current limiting regulator.
27. Resistance.

It need hardly be mentioned, that the elimination of danger during maintenance must always be considered in arranging the plant.

The chief rule is that the connections shall be made as clear as possible. This is of inestimable value to the staff in case of disturbances. If the connections of the power station have been well designed, and a minimum of apparatus is contained, a clear and easily supervised arrangement of the switchgear can be obtained. In stations which can be erected on open spaces, in view of more convenient attention and smaller building costs, it is advantageous to install the switchgear on a single floor. In the event of this being so, the connections of the station can then be most easily traced from the plan. Should the space available be limited, and a design in which the apparatus is installed on more than one floor is used, the connections can be most easily followed from the cross section of the station.

The arrangement of the apparatus in independent units led to the adoption of unit construction for the buildings; these should be so placed that in case of future extensions, the necessary units can be added to the existing buildings in order to house the new plant. This is the simplest way of taking into account the possibility of future expansion.

As previously mentioned, the switchgear in modern installations is subject to stresses which have considerably increased from those formerly usual. Experience arising from the increasing short-circuit output of stations, besides leading to reinforcing the switches, also led to the switches being mounted in cells, thus localising any disturbance. The cells are so built that, should a switch explode, no damage could spread to the interior of the building but the gases formed escape, through doors or windows, into the open air without doing further damage. To shorten the duration of an outbreak of fire, each cell is provided with an outlet which leads into the sump into which the oil flows. It may be

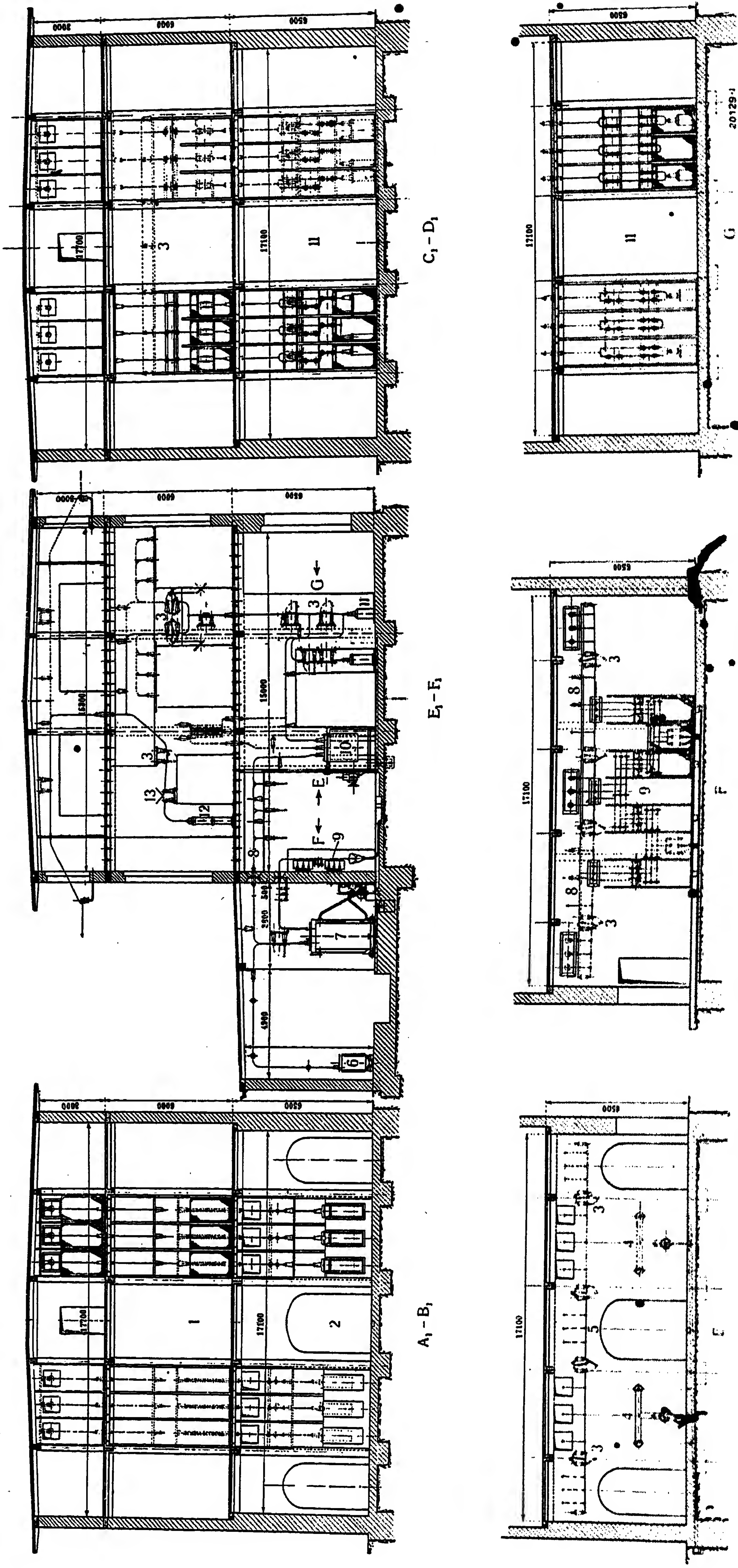


Fig. 30. Transformers and switchgear for 50,000 V at Bois Noir Power Station.

1. Space for reserve resistances.
2. Oil switches with adjustable resistances.
3. Isolating switch.
4. Oil switch control.
5. High-tension bus-bars for transformers.
6. Earthing choke coil.
7. Main transformer, 7500 kVA.
8. Transformer bus-bars 50,000 V.
9. Transformer bus-bars 6500 V.
10. Oil switch 50,000 V.
11. Current transformer.
12. Water resistance.
13. Horn gap lightning arrester.

mentioned that the cells are made proof against high pressures and as smoke-tight as possible, hence they are completely shut off from the remainder of the plant. Each cell contains all the oil-immersed equipment belonging to one power unit; the cells must be divided from each other by fire-proof doors. As a result of this protection, which is of a similar nature to that provided by the bulkheads in ships, any disturbance is limited to the power unit first affected.

The control apparatus as, for example, the switch controls, is mounted in a room or in the gangway outside the cells, thus preventing any pressure-carrying part from being approached (Fig. 32). The operation of the switches can consequently be carried out by hand without danger, the cells being only very rarely entered for inspection purposes and, on such occasions, the power unit connected to the cell is always switched out.

With extra high-tension installations, the large dimensions of the cells would lead to expensive buildings for the switches, if cells were used. It has therefore been decided to make all the switchgear water-proof so that it may be installed in the open (outdoor switchgear). This type originated in America but has now been introduced into Europe. Brown, Boveri & Co. build apparatus of this special construction which is suitable for any of the pressures common to-day. For particularly trying climatic conditions, and for cases where the administration for some reason or other object to the out-door type; Brown, Boveri & Co. have developed apparatus between this type and the type suitable for an enclosed cell. The cell bushings are thus saved, the oil-immersed apparatus such as switches, current transformers, etc., being so arranged that only the tanks are in the cells. The tops of the tanks of the apparatus concerned are particularly strongly made and form the covers for the cells. The cells are provided with oil outlets and must allow any excess gas pressure to escape rapidly to the outside air.

For some time past, flashovers between the various phases have been prevented by separating the leads of the complete plant by means of partitions. This division resulted in the installation becoming very expensive and difficult to supervise, while the possibility of false connections was greatly increased. Modern practice has reverted to the open type. The distance between the lines has been increased to ensure that flashovers between the phases

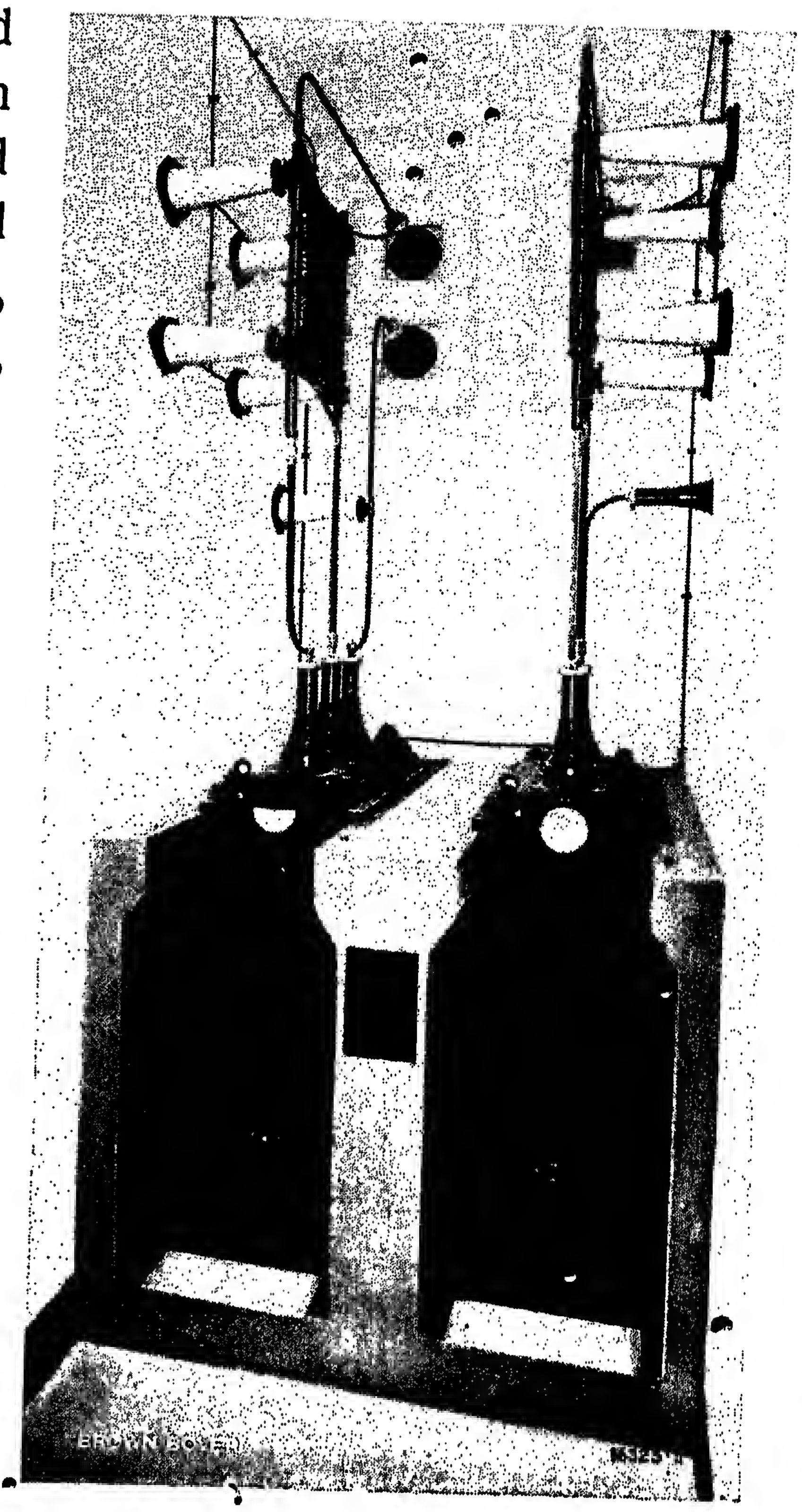


Fig. 31. Switch cells at the Barberine Power Station of the Swiss Federal Railways.

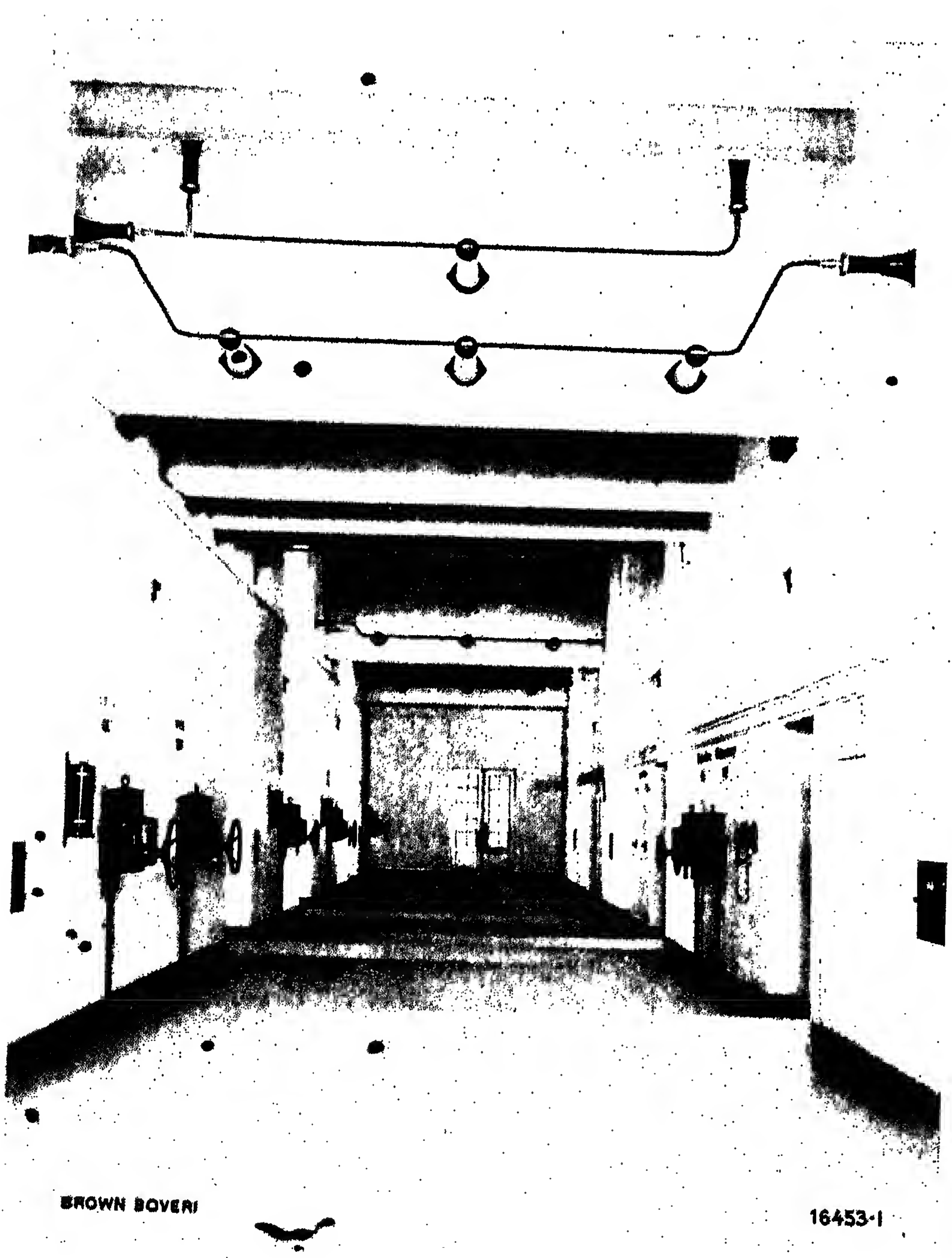


Fig. 32. Gangway for switch control at the Barberine Power Station of the Swiss Federal Railways.

(On the wall are the Brown Boveri magnetic remote controls for the oil switches.)

Fig. 33. High-tension switchgear of the Pescara Power Station (Italy).

will not occur. Partitions may be introduced between the various panels, but, by judicious grouping of the leads, they can be entirely dispensed with. The Pescara Power Station (Fig. 33), equipped by Brown, Boveri & Co., is a good example of this kind of plant.

A precautionary measure, to which too much attention cannot be paid, is the clear marking of each panel when similar panels are arranged in a row; only by such means can serious mistakes and accidents be avoided. The Pescara installation is a model in this respect also.

The increasing output and the coupling of power stations together have led to the circuit breakers being designed for the short-circuit current rather than the working current (see Brochure 782 E, "Oil circuit breakers of large rupturing capacity").

One of the first tasks when designing a modern power station which is to operate with an existing system, is the calculation of the rupturing capacity on short circuit.

A simple and sufficiently accurate method for the practical calculation of the short-circuit current of systems connected in parallel has been given in the Revue BBC, 1920, Nos. 5 and 6, also in brochure 681 F, "Calcul des courants de courts-circuits, et de leurs effets dans les réseaux à courant alternatif"

The type of the insulators, the distance between the conductors of each phase in the switchgear and also the type of the current transformers must be chosen with respect to the amplitude of the momentary short-circuit current. Under certain circumstances it may be necessary to install reactances for damping the current on short circuit.

The adequate protection of an installation from the effects of excessive potentials has been ensured by the systematic, scientific investigations of Brown, Boveri & Co. To-day a suitable solution can be offered for each instance that arises. The results of these investigations have also become of value in influencing the construction of the machines, especially the transformers. The increased strength of the windings, protection rings for distributing the field at the ends of the high-tension windings, etc., may be mentioned here.

Brown, Boveri & Co. have also assisted in finding a solution for another problem, which concerns earth connections. For a long time the earthing leads had not been dimensioned or installed with the amount of care desirable. Numbers of accidents have occurred which in future may be avoided if the results of the investigations are borne in mind. (See "Bulletin des Schweizerischen Elektrotechnischen Vereins", 1925, Nos. 7 and 8).

7. CONTROL ROOM.

It was formerly usual to mount the apparatus necessary for the control of the generators in a manner similar to that used for the controls of the hydraulic parts, i.e., on pedestals or small switchboards near to the machine itself. This arrangement is still employed in very small power stations which

contain only one or at the most two sets. As the number and size of the machines, and also the output of the station increased, the requirements necessitated that all the electrical apparatus should be mounted in a place from which the complete machine room could be supervised. This then constitutes the control stand. The electrical apparatus is built into a desk and mounted on a stage or gallery from which the attendant can overlook the whole of the machine room. Examples of this arrangement are found in the Augst Power Station (Fig. 8) which was put into service in 1912, and the Hakavik Power Station (Fig. 37). As time went on, the control apparatus and measuring instruments increased, so that this arrangement was no longer sufficient. The noise caused by the machines was often so great that the attendants had difficulty in communicating with one another. It was then decided to remove the control stand from the machine room and install it in a room by itself. The attendants could then overlook and direct the service without the inconvenience of the noise. All necessary operations could therefore be carried out in quietness and with greater judgment. The phenomena occurring with any disturbance caused no excitement, as the attendants were completely shut off from the machine room.

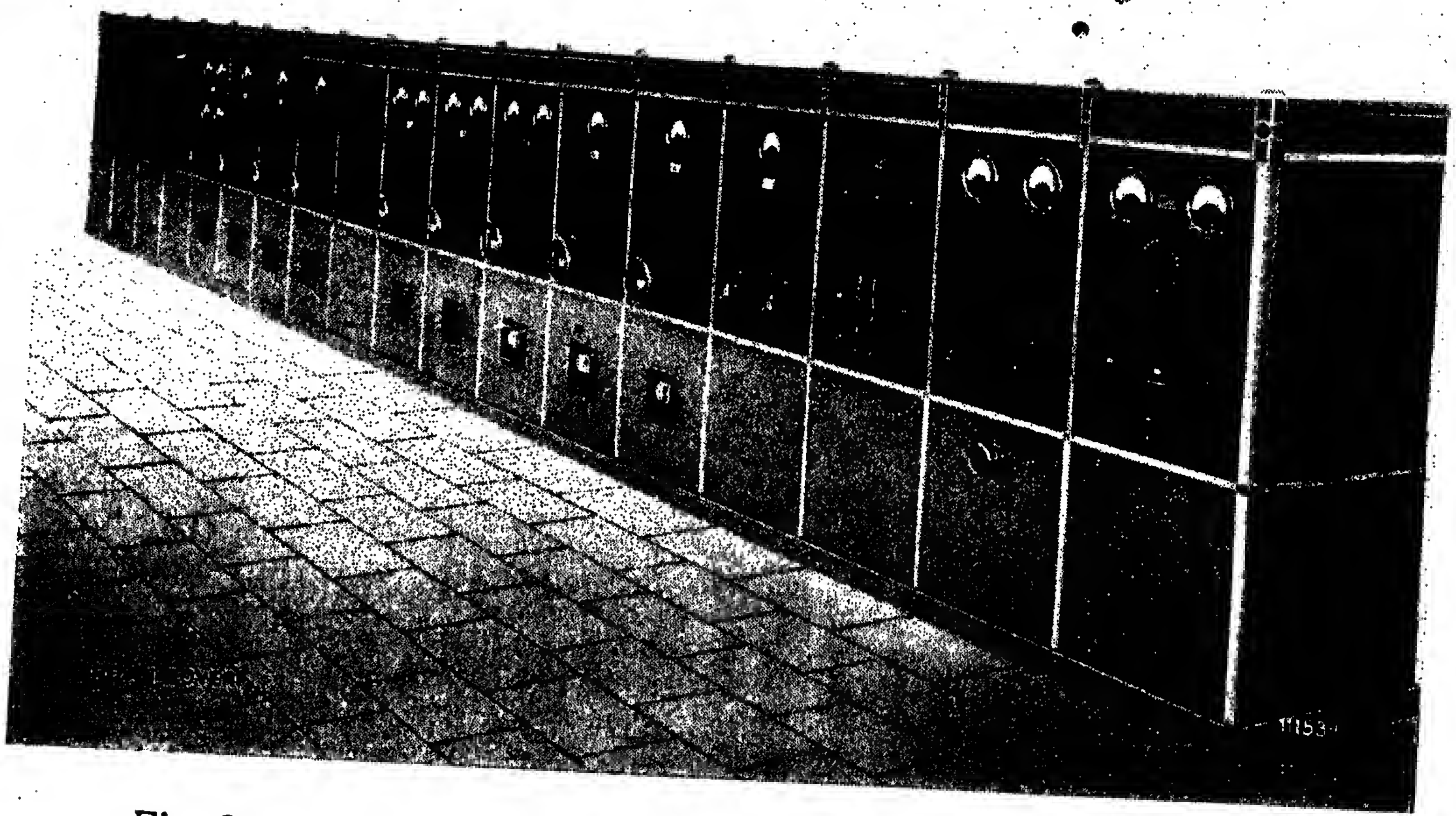


Fig. 34. Switchboard with panels for low-tension switches.

The whole arrangement of the control room must be such that the maximum quiet, light, and general cleanliness prevail, these factors being the chief precautions against mistakes. The equipment of the desks and boards is also important. The division of the panels must correspond to the distribution chosen for the various units of plant. They must be designed so that the inspection of all apparatus and repairs to any panel can take place without causing a disturbance to other parts of the installation. The principles relating to the ease of supervision of the leads apply in the control room as well as for the main conductors. The difficulties to be overcome by the constructor are, however, considerably greater, as the number of control and instrument leads which have to be laid to the control room is enormous. The installation of the leads in a correct manner requires careful, detailed attention when the station is being designed. In many modern power stations the space below the control room is used for grouping the leads and distributing them in a suitable manner to the desks and boards above.

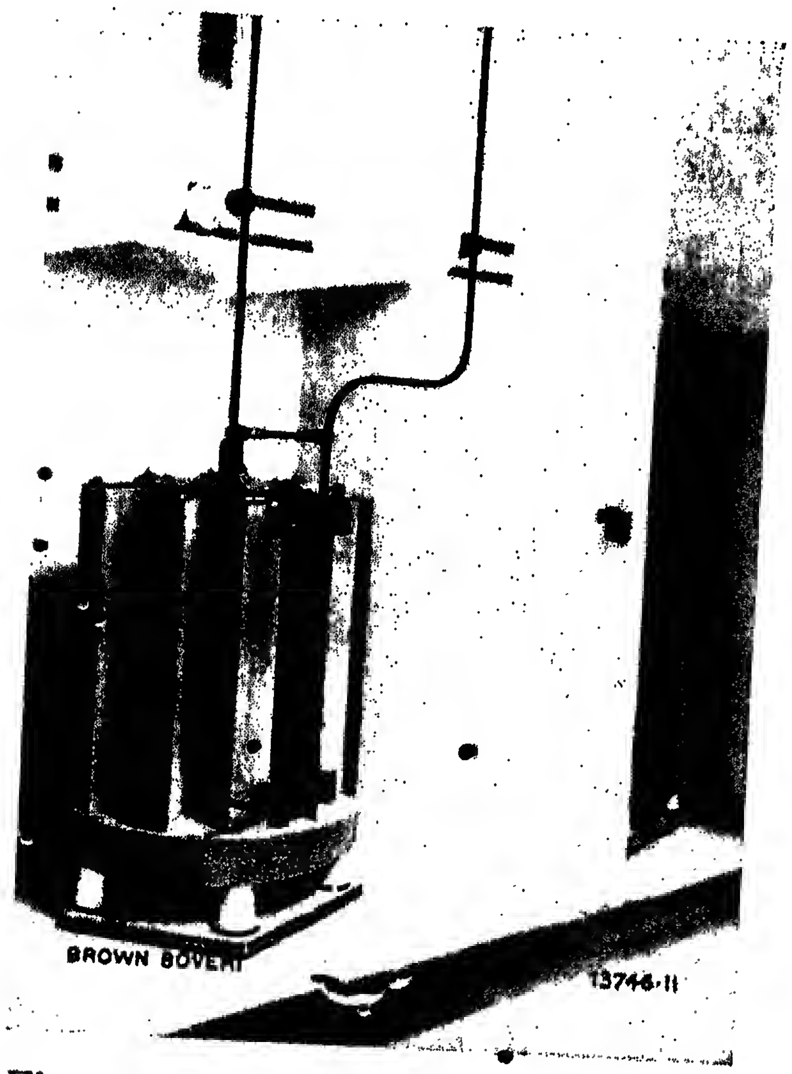


Fig. 35. Reactance coil for damping short-circuits, as installed in the Mühleberg Power Station of the Bernese Power Supply Company, Berne.

All important switching operations can be made from the control room by means of remote control. A signal lamp is fitted to each control switch to show if the remote control acts properly and makes the correct connection when operated. The control switch or contact maker developed by Brown, Boveri & Co. for this purpose, is characterised by its robust construction, simplicity and the small space which it requires. A free-return coupling is provided to prevent the switch being repeatedly closed on an existing short circuit (pumping of the switch), which would be unavoidable if the switches had excess current releases and the attendant held the lever in the "on" position for a long time.

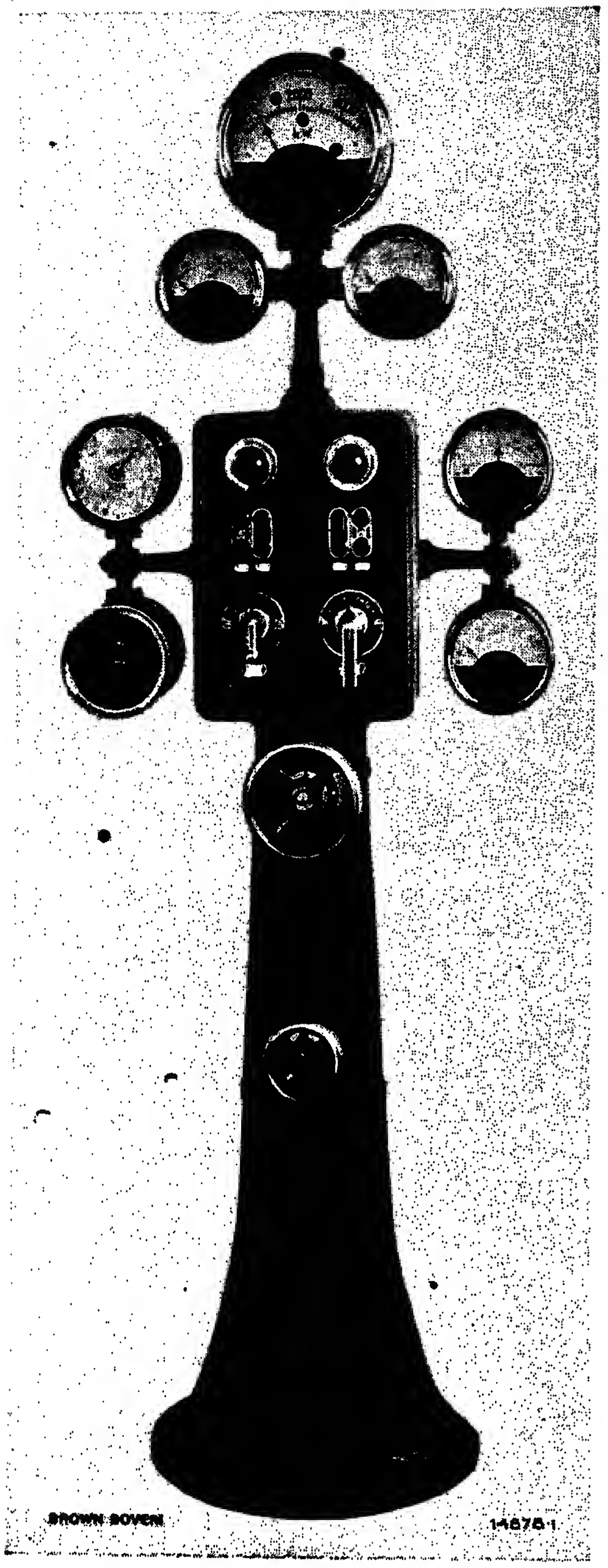


Fig. 36. Switch column.

The contact maker is fitted with a locking coil so that, when once it has been moved to the "on" position, the contact maker cannot be returned to the zero position until the switching operation has occurred. By these means the interruption of the switching-out current by the control switch is prevented, thus protecting the switch from the destructive properties of a direct-current arc. In the Brown Boveri system of remote control the control current is interrupted by the control mechanism itself.

An automatic lay-out of the plant is mounted in the control room of large power stations in order that the positions of the switches may be seen at any time. Every circuit breaker and every isolating switch is fitted with a position indicator, i.e., a small apparatus which changes its direction of rotation in a similar way to a direct-current motor when the current is reversed in the field or in the armature. The angle turned through is limited on either side by stops. A pointer or disc mounted on the spindle shows whether the switch is opened or closed. A spring enables a zero position to be provided; the indicator assumes this position as soon as the current is interrupted, so that any fault in the signal installation is shown automatically. If the automatic diagram is to be of real value, it must be absolutely reliable. The position indicator must be made and tested with special care, the surplus torque, i.e., the difference between the torque produced and that necessary to overcome friction (which should be a good margin in order to ensure reliability), and the connections of the apparatus being taken into account. Fig. 39 shows the control room and diagram board for the Bois Noir Power Station near St. Maurice; this station was designed and equipped by Brown, Boveri & Co. for the Lausanne Municipal Electricity Supply.

Besides providing optical signals, which show any change in the position of a switch, it is advantageous to install alarms also: these attract the attention of the operator, who may be engaged in other work at the time.

The instruments provided for the various panels chiefly depend upon the requirements of the service, but in the interests of supervision and reliability, the apparatus provided should be a minimum. Profile instruments are frequently provided in order to save space. All measuring circuits must be provided with testing terminals which allow the

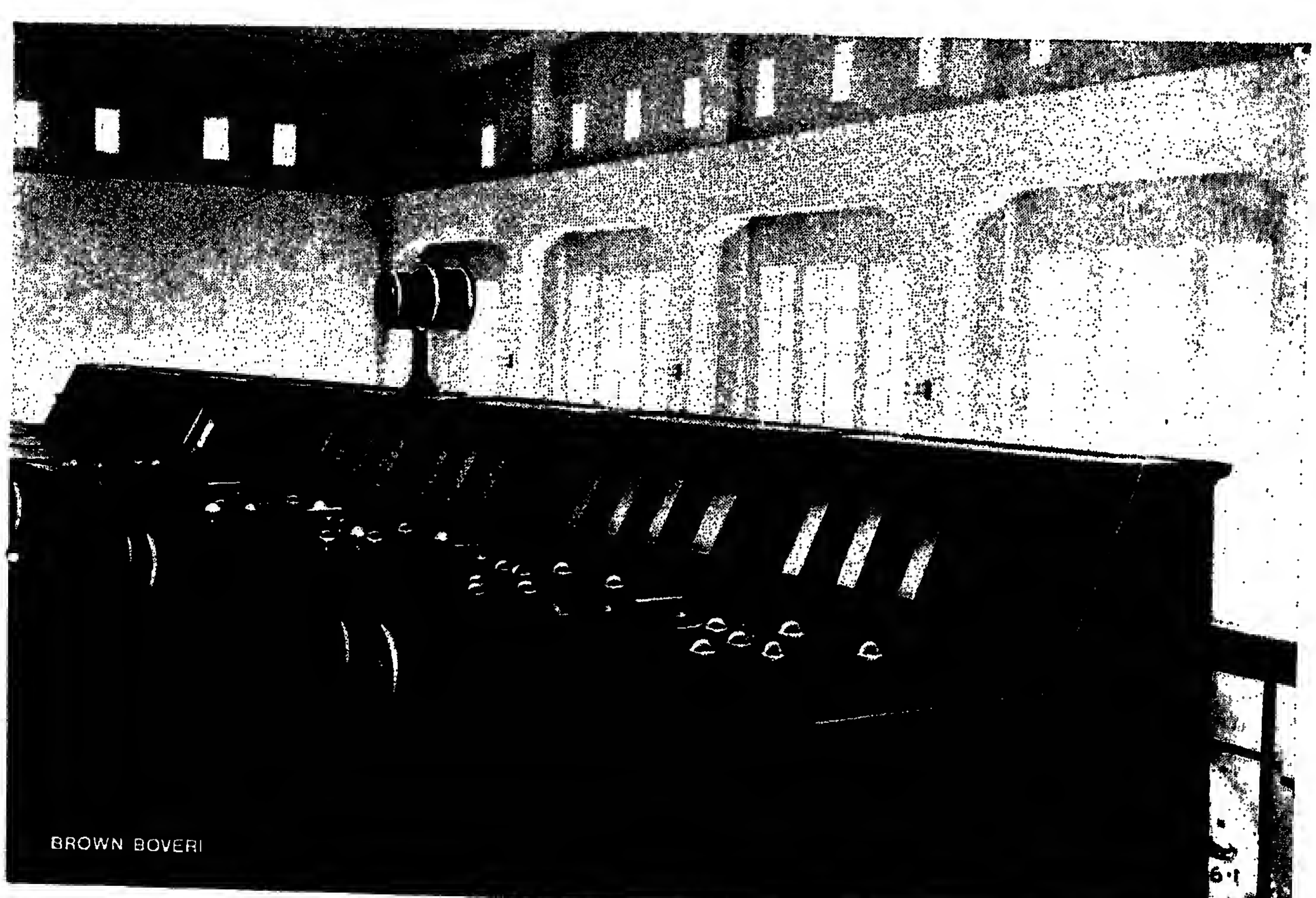
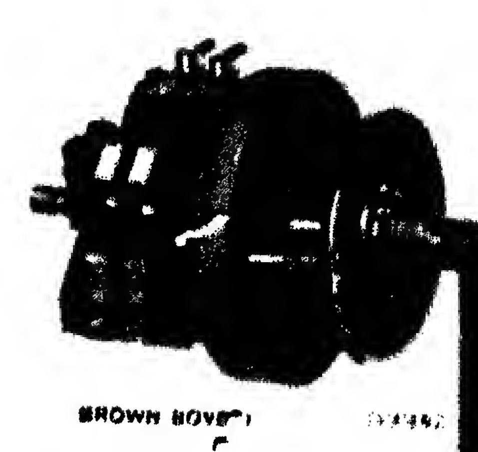


Fig. 37. Switch desk installed on a gallery (left).

Fig. 38. Control switch for remote control (right).



calibrating instruments to be connected at any time without disturbing the service. The instruments supplied from a current transformer may also be connected by a system of terminals which renders possible the short-circuiting or exchanging of any instrument at any time.

If a fuse becomes damaged the control circuit may be without pressure for a long time; hence the unit in question has no protection. To draw attention to this, it is recommended that in important panels a minimum voltage relay be fitted behind the fuse, near the place where the auxiliary pressure is tapped; the relay should actuate a bell. In order to enable the auxiliary circuit of each panel to be tripped separately as previously mentioned, a suitable panel for the auxiliary circuit must be provided in the control room. As tripping when not under current is required, no switches are necessary but the fuses which have to be provided for cutting out a short circuit, are sufficient. The chief consideration is the grouping of the installation to correspond to the units of the power station. The previously general method of mounting these fuses in the respective desks and panels is not to be recommended, as it is not possible to isolate the panel completely for purposes of inspection or repairs. When dealing with a closely filled place, e.g., the switch desk, it must be pointed out that the absence of every pressure-carrying part is a great advantage to the inspecting staff.

With synchronising devices, especially in power stations containing various bus-bar systems, great attention must be paid to see that no false connection is possible. The voltmeter change-over switches formerly employed are to be completely avoided; instead, a synchronising switch in the form of a turn switch or plug having only two positions ("in" and "out") is mounted on each alternator or coupling panel. To prevent more than one panel being connected to the central synchronising instrument (synchroscope with double voltmeter or summation voltmeter with lamps, etc.), a common switch handle, which can only be removed when in the "off" position, is provided for all panels. The pressure on the bus-bar side can be supplied from each bus-bar system from one potential transformer. In order to avoid false connections, this pressure is led over a pilot switch depending upon the position of the isolating switch of the panel concerned. If, however, there is sufficient space in the switchgear, it is recommended to combine a potential transformer with each side of every circuit breaker which is used for parallel connections. This solution is a little more expensive, but in service it is recognised to be by far the safest. A great simplification in operation results through the use of the Brown Boveri automatic synchroniser. This apparatus, which was developed from the Brown Boveri quick-acting regulator and is protected by patents, operates the remote control of the oil switch as

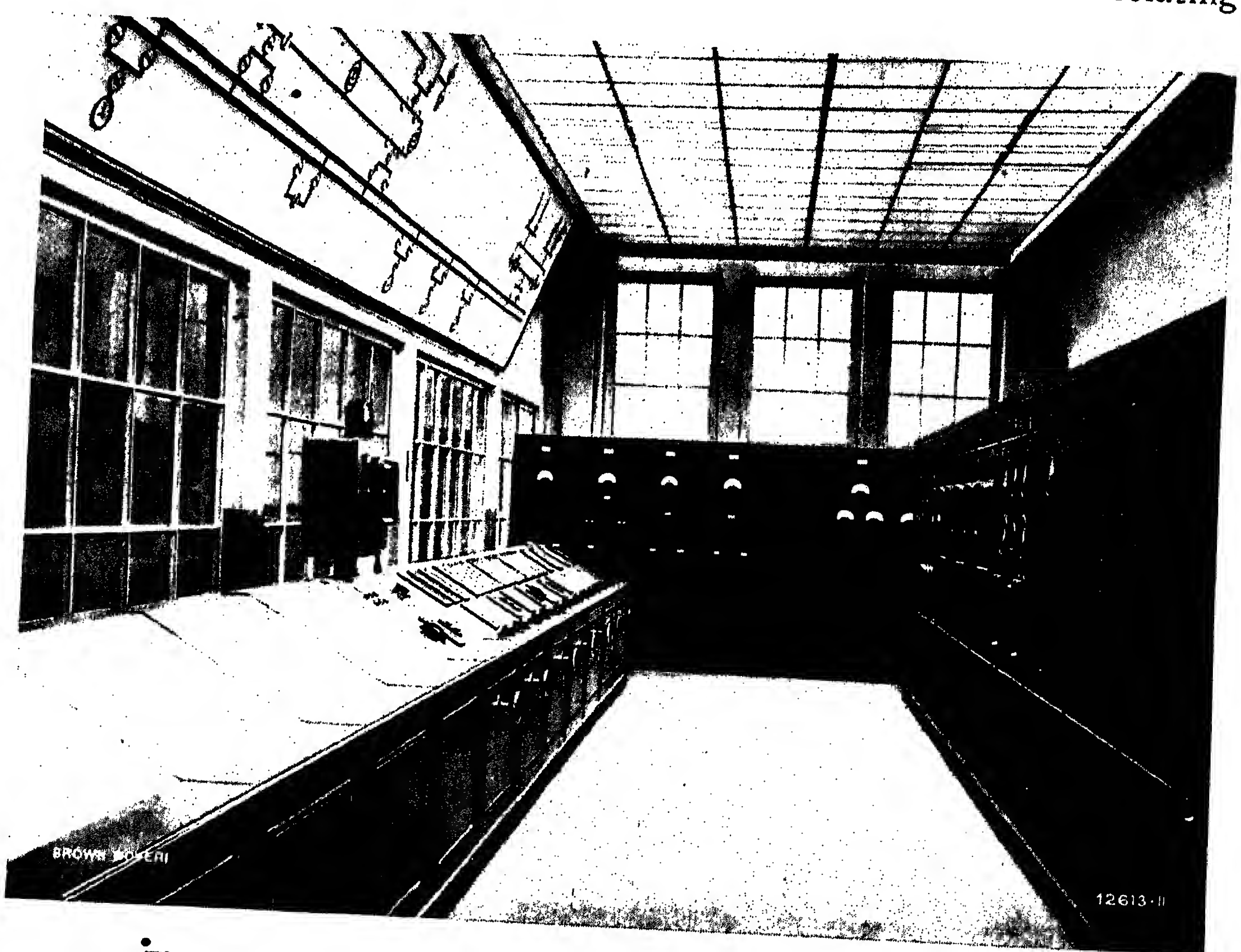


Fig. 39. Control room in the Bois Noir Power Station, St. Maurice in the Rhone Valley.

soon as the panels are in synchronism.

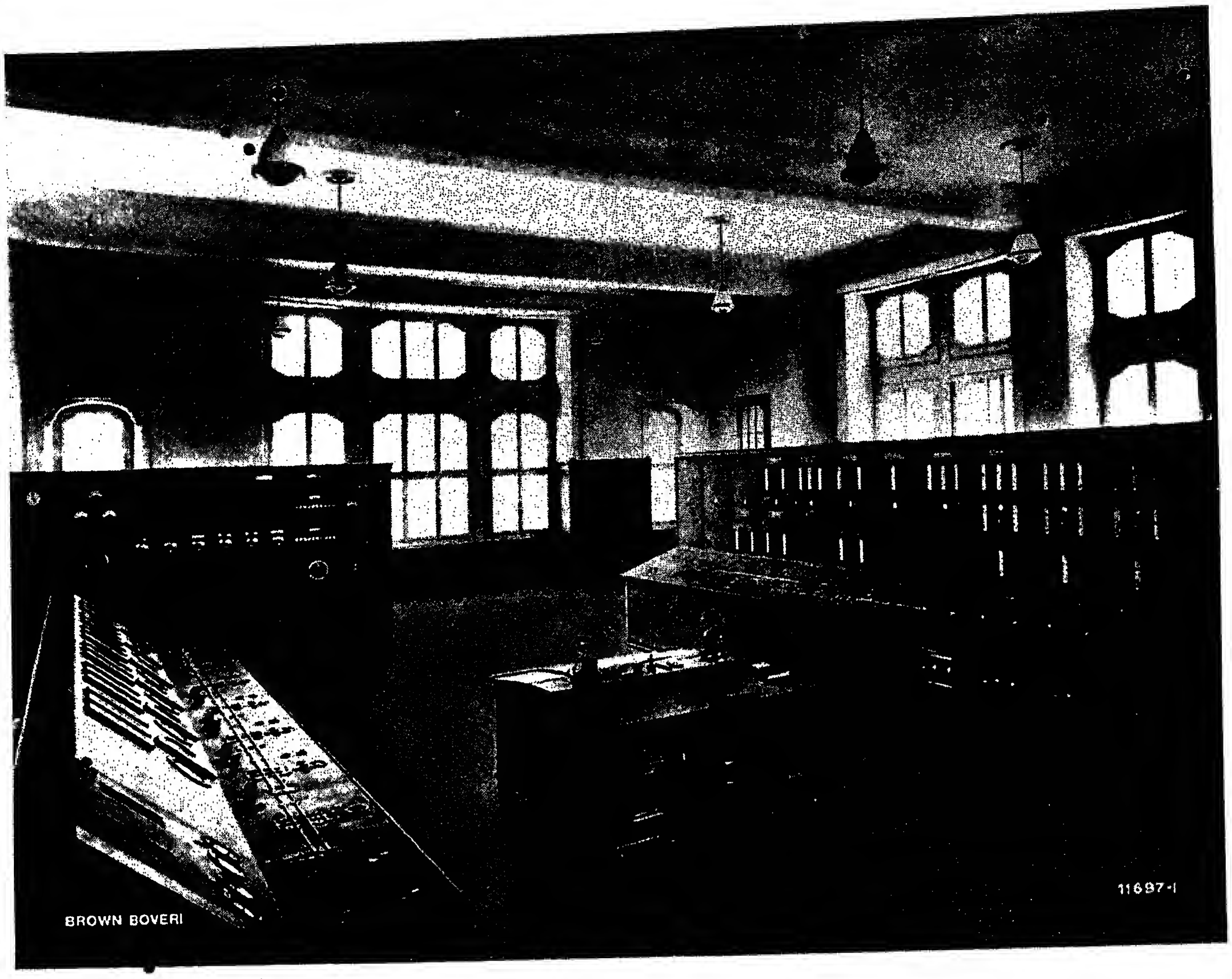


Fig. 40. Control room of the Goesgen Power Station of the Olten-Aarburg Supply Company.

The initial cost of the alternators and transformers has, naturally, increased as the unit output has become greater, so that regular service and prevention of damage must be ensured in every way possible. It has, therefore, become customary to provide the machines with distance thermometers. Formerly, thermo-elements were frequently used; they are, however, very delicate and often give wrong values. Hence resistance elements, built into the machine at places which are expected to develop the maximum temperature, have become more and more employed. Measurements are made by means of a Wheatstone bridge, the galvanometer variation of which corresponds to the increase of resistance of the measuring element; hence the scale of the galvanometer may be divided directly into centigrade degrees. A push button device is provided to ensure that only one element at a time can be connected to the bridge. If the temperature of the transformer oil must be measured, the apparatus may be supplied with direct current at a low pressure. If, however, the resistance element is to be mounted near the windings, it is recommended that, as a protection against flashover from the high tension side, the elements should be connected to the measuring device through protecting transformers. In this case alternating current must be used for determining the temperature.

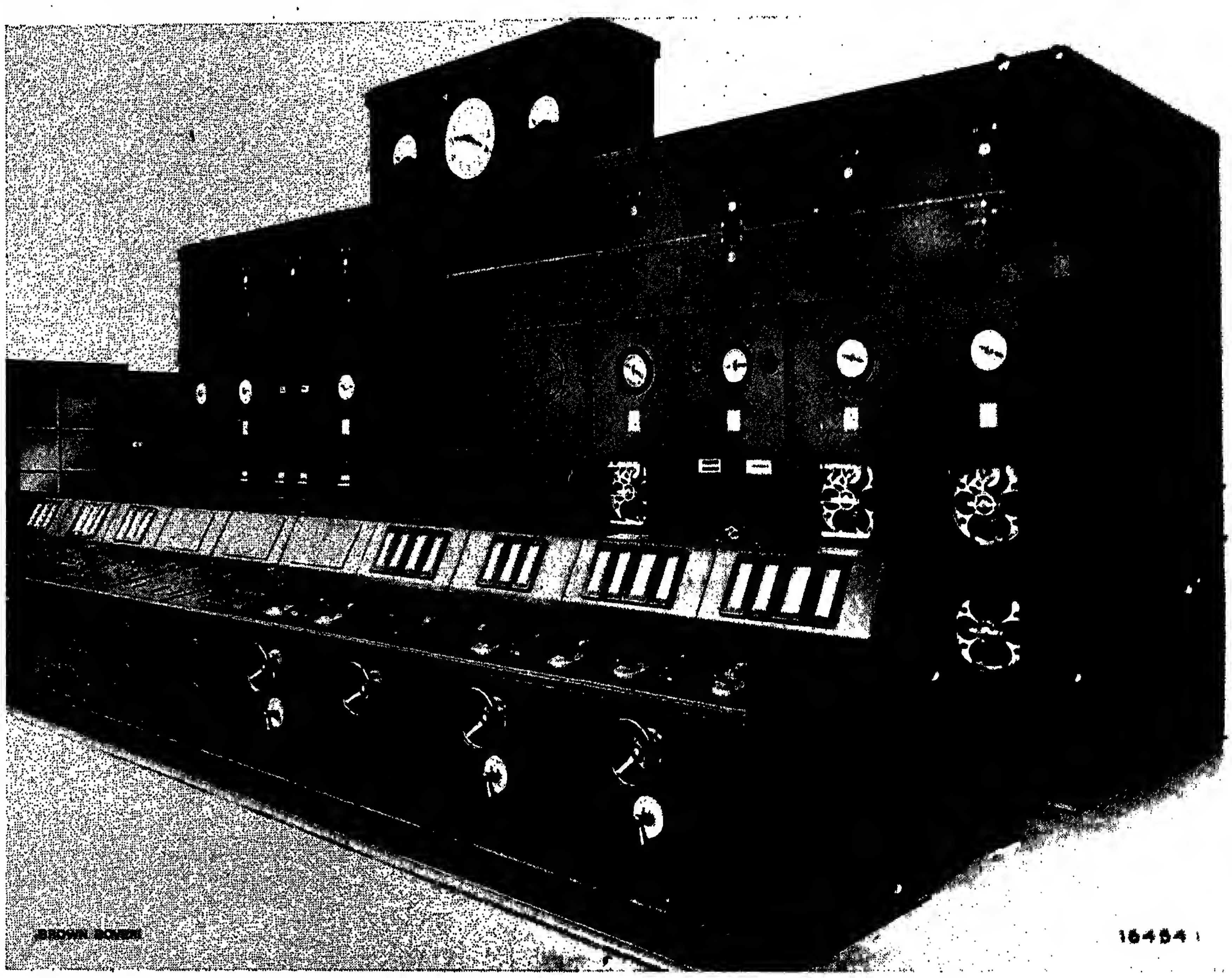


Fig. 41. Control room of the Barberine Power Station of the Swiss Federal Railways.

Besides this temperature measuring device, a contact thermometer, which actuates an alarm when the maximum permissible temperature is exceeded, is also fitted. The comparatively large number of alarm bells has led to all the conductors being connected to one indicating box operating only one bell. The bell attracts the attention of the attendant, while the indicator which has fallen down shows the kind and position of the disturbance.

The devices in the control room can be so installed that only one man is necessary for directing the largest power station. Care must be taken to see that the attendant in charge can observe all of the desks and boards in the control room from his central position. The lighting of the room is of great importance, and reflections from the numerous instruments must be prevented, so that there is no hindrance to the observer when taking a reading. It is clear that these conditions require an exceptionally careful choice of the positions of the desks and boards; this can only be guaranteed by expert constructors.

It must also be mentioned that the attendants in the control room must be able to communicate with the outer world, as well as other parts of the installation as, for example, the machine room and the switch room. If the general arrangement of the power station will permit it, the control room should be so placed that the attendant can overlook the machine room and signal to the staff engaged there. Owing to the great extent of a modern switchgear plant, an internal telephone system is unavoidable.

In a large power station the control room may be regarded as the centre of the organisation, from which innumerable auxiliary lines radiate (similar to nerves) to indicate the occurrences at every part of the installation.

8. AUXILIARY SERVICES.

A large number of auxiliaries are necessary for the satisfactory running of a modern power station. Among the most important of these is the control battery. It supplies the direct current needed by the power station for all remote controls, tripping the circuit breakers, signalling, etc., and forms a source which is independent of outside supplies and of its own machines producing the alternating current. It is advisable to dimension this storage battery so that it can supply the lighting needed in the station for a short period during emergencies. For a number of important lamp-circuits, the switching over to the battery is carried out automatically as soon as the alternating current supply fails.

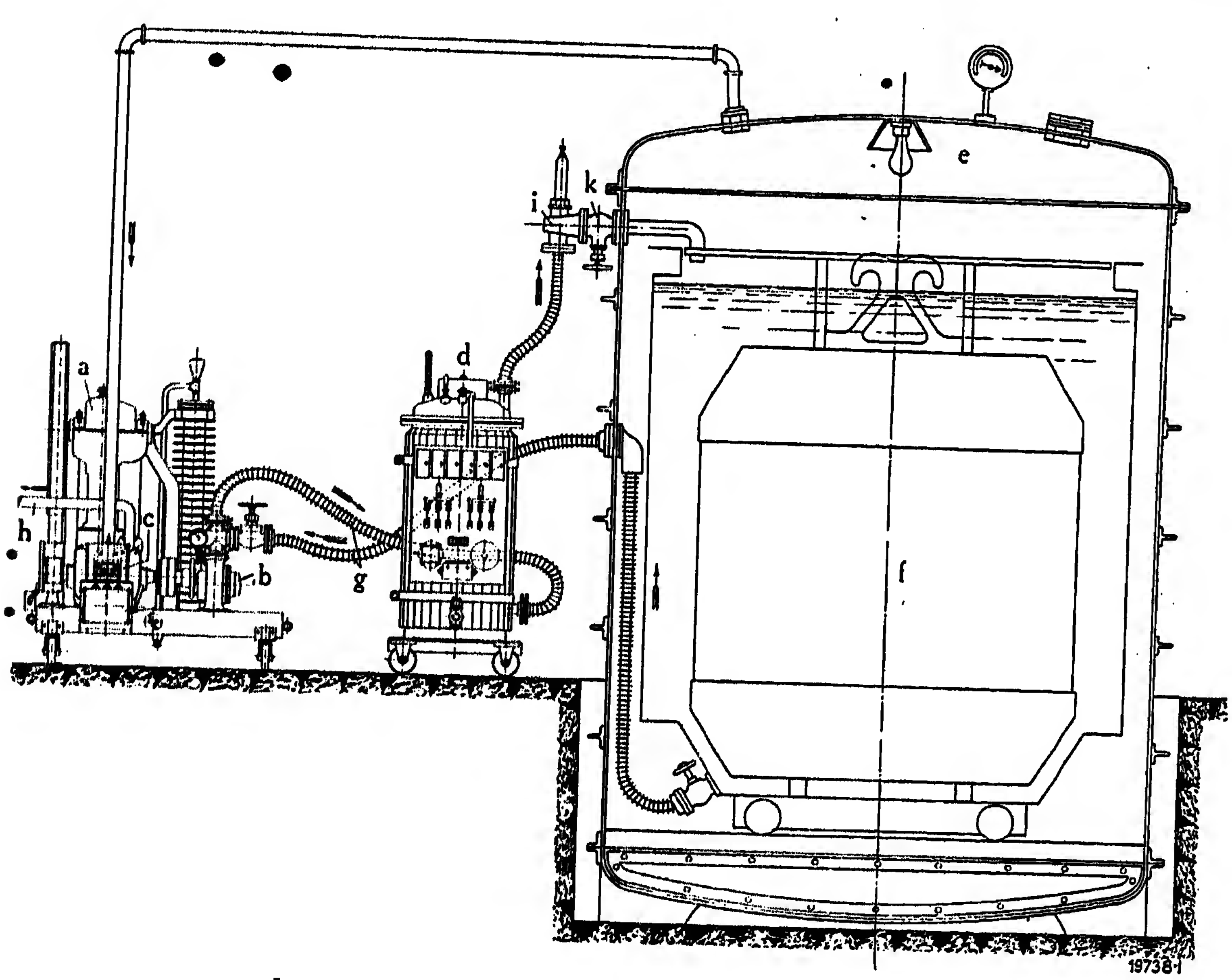


Fig. 42. Vacuum oil-drying equipment and vacuum tank.

a. Vacuum pump.
b. Oil pump.
c. Driving motor.
d. Continuous heater for oil.
e. Vacuum.
f. Transformer.
g. Oil mains.
h. Exhaust of vacuum pump.
i. k. Junction valves.

The equipment of the power station with lifting gear, i.e., machine-house crane, etc., for erection and overhaul will only be mentioned for the sake of completeness.

As the amount of oil-containing apparatus in a modern power station is very great, it is clear that suitable arrangements must be made for handling the oil used for insulation purposes. One of the most necessary

parts of the equipment is an installation in which the transformers with their oil filling can be dried out under vaccuum. Brown, Boveri & Co. have developed equipment for this purpose, which embodies the results obtained from many years' experience. Fig. 42 shows a complete oil-drying installation, in which the whole transformer is placed in a tank, the latter then being exhausted by an air pump. This installation is completed by providing an oil filter (Fig. 43) in which oil that has been in service for a considerable time may be freed from sludge and foreign matter and also, to a great extent, from water.

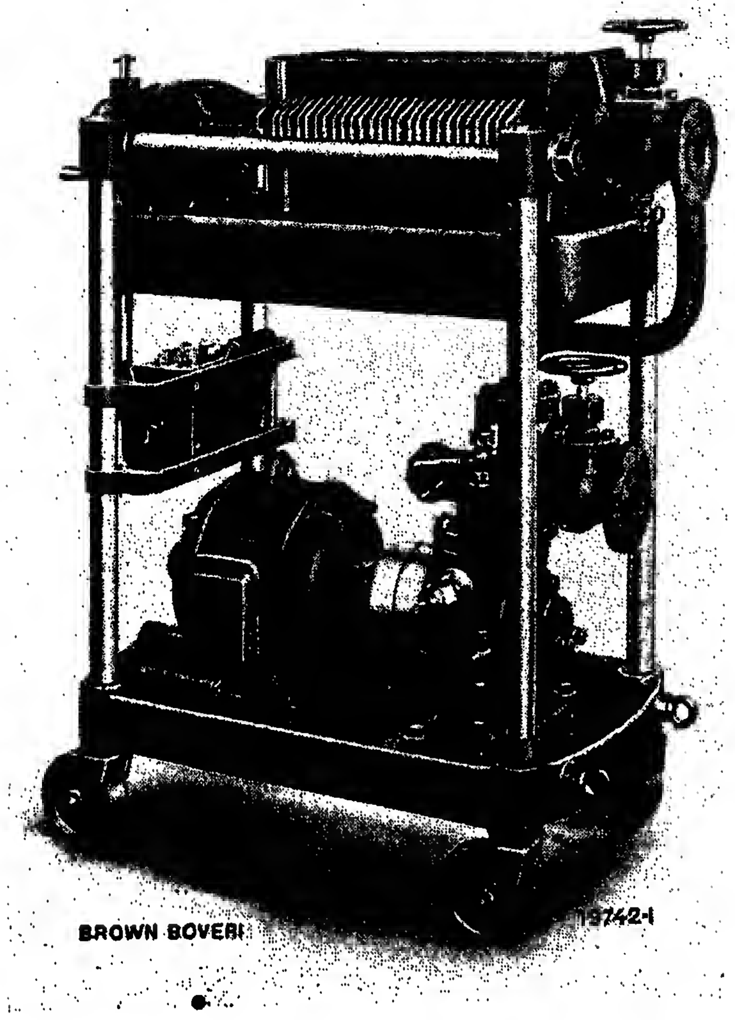


Fig. 43.
Oil filtering apparatus.

In smaller power stations it may be more economical to provide the few transformers with air-tight tanks and a special interchangeable air-tight cover instead of installing the plant shown in Fig. 42. In this case the transformers can be dried-out in their own tanks.

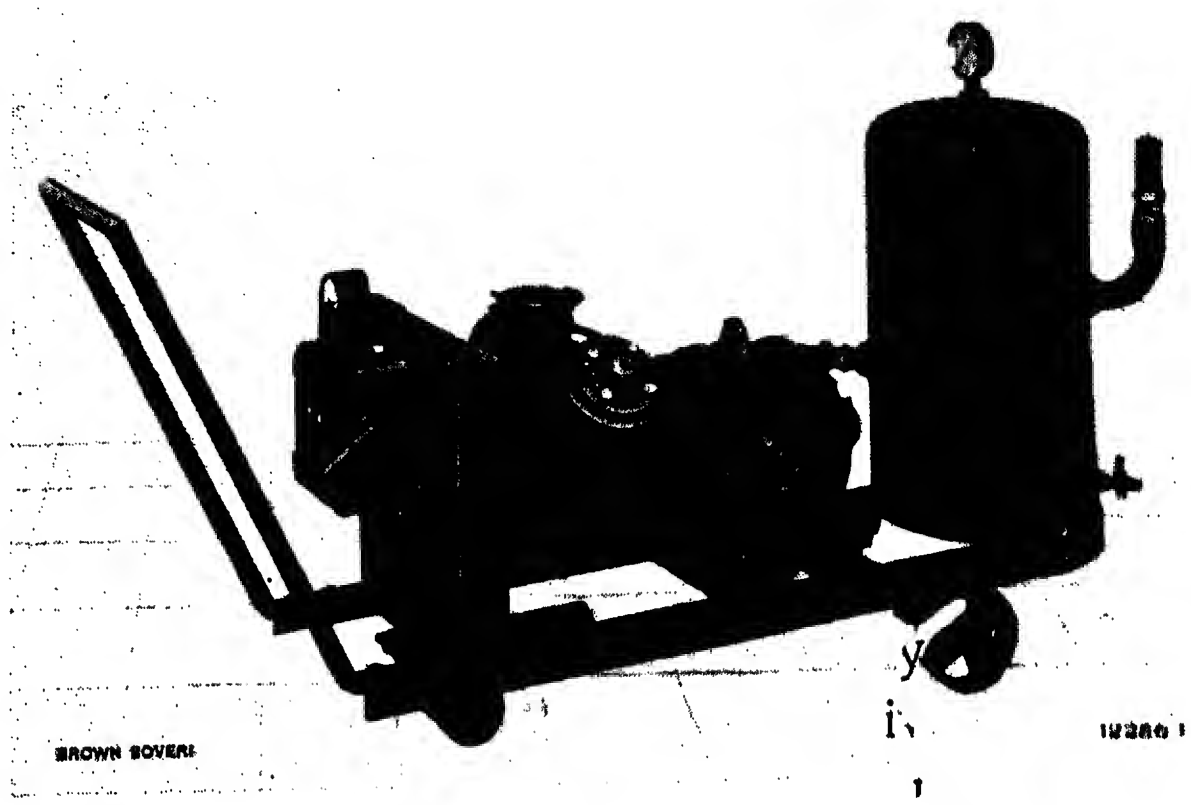


Fig. 44.
Brown Boveri portable motor-compressor.

It is advantageous to provide suitable means for the storage of the different kinds of oil required, e.g., that for switches, transformers, regulators, lubrication, etc.; these reservoirs should be connected to the most important apparatus by means of a system of pipe lines.

All these general auxiliary services must be situated at a central part of the station, where a rest room for the staff and the necessary sanitary arrangements must also be provided. The switch gear and machines are frequently housed in three buildings which are architecturally separate, as for example, the Barberine Power Station of the Swiss Federal Railways (Fig. 4).

9. AUTOMATIC POWER STATIONS.

The necessity of saving the high wages as much as possible has led the management of power stations in all countries to consider the installation of automatic stations. There is a growing tendency to convert existing plants to this type and to install more automatic stations. According to the local conditions, automatic power stations may be divided into three classes: stations without permanent inspection, remote controlled stations, and unattended stations. The stations without permanent attendance are those which are put into service or shut down by hand, but are so equipped that the attendant is not required at other times and can thus hold another position in the vicinity, such as mechanic, tradesman, etc. Every modern power station which is equipped with Brown Boveri protective devices (protective relays and current limiting regulator) is able to run without permanent supervision. In stations

without permanent attendance it is simply necessary to add some apparatus which, in the event of a disturbance, will switch out the electrical part and at the same time shut down the hydraulic part of the installation. A signal apprises the attendant of every disturbance. As previously mentioned, the station must be set into service or switched out by hand; the necessary orders may be transmitted by telephone, or may be obtained from a fixed time table.

Remote control stations also work without permanent attendants. With these stations, however, the control room is removed from the station and transferred to the main station or to the district supplied by the station, where permanent attention is always provided. The staff here, then supervises the remotely controlled station, placing it in service and shutting it down by means of the remote control devices. As a large number of control lines are necessary between the main station and the subsiduary station, for the measuring instruments and signalling apparatus, this type has, until recently, only been applicable when the two stations are separated by a small distance. However, this drawback has now been eliminated by the development of the supervisory control system. This renders it possible to maintain complete control over outlying auxiliary stations (including starting, stopping, adjustment of load, etc.) by the use of only three or four pilot wires between the control station and the unattended stations. It may here be pointed out that the Brown Boveri system possesses an advantage over other systems of supervisory control, in as much as it enables reliable readings of instruments to be transmitted to the control station and there received on the ordinary type of indicating instrument whereas in other systems, the instrument readings, if transmitted at all, are only obtainable in steps.

The starting up or shutting down of purely automatic or unattended power stations results automatically; e.g., it depends upon the water level in the head race, it occurs at definite times, or finally, upon the arrangements made by the management in the main power station. If the automatic station is connected with the main station by an independent high-tension line, it may be put into service or shut down by means of this line. Should it be impossible to connect the automatic station to the distribution system by its own line, the starting up or shutting down may be effected by operating a push button in the main station. In this case two pilot wires between the two stations are necessary. Completely automatic power stations are to be recommended in every case where wages are high or if the stations are far apart. Attendance is completely unnecessary, and no staff need be stationed in the neighbourhood. It is sufficient if the unattended stations are visited during the periodical inspection of the distribution system.

The arrangements developed by Brown, Boveri & Co. are patented. Already there are various unattended stations under construction or in service. In all plants installed by Brown, Boveri & Co. care has been taken to see that all automatic operations are performed in the same sequence as in hand controlled stations. The completion of one operation enables the succeeding one to be started, but no operation can occur until the preceding one is completed. Interlocking arrangements prevent all false connections, whereas with the rotating drum type of switch used elsewhere, the various operations are released one after the other, and no absolute guarantee can be given for the retention of the correct sequence. Already numerous unattended power stations exist in America, but in Europe a timidity of automatic devices has existed up to the present. This lack of confidence is completely unfounded; Brown, Boveri & Co. use only the most suitable arrangements of well known relays and devices which many years' service have proved to be satisfactory.

10. CONCLUSION.

There is still much which could be mentioned relating to modern hydraulic power stations and their equipment. Each piece of apparatus which leaves the Brown Boveri Workshops is an example of careful construction which embodies the experience obtained. It would be outside the range of this article to enter into all details, as it deals only with the various questions arising and the most economical solution. The finding of the best solution for each individual case must be entrusted to the designing engineer and requires an extensive general technical knowledge.

Owing to their large staff of experienced engineers, Brown, Boveri & Co. are able to undertake to supply not only the complete electric machines and apparatus, but also to design and install complete switching stations.

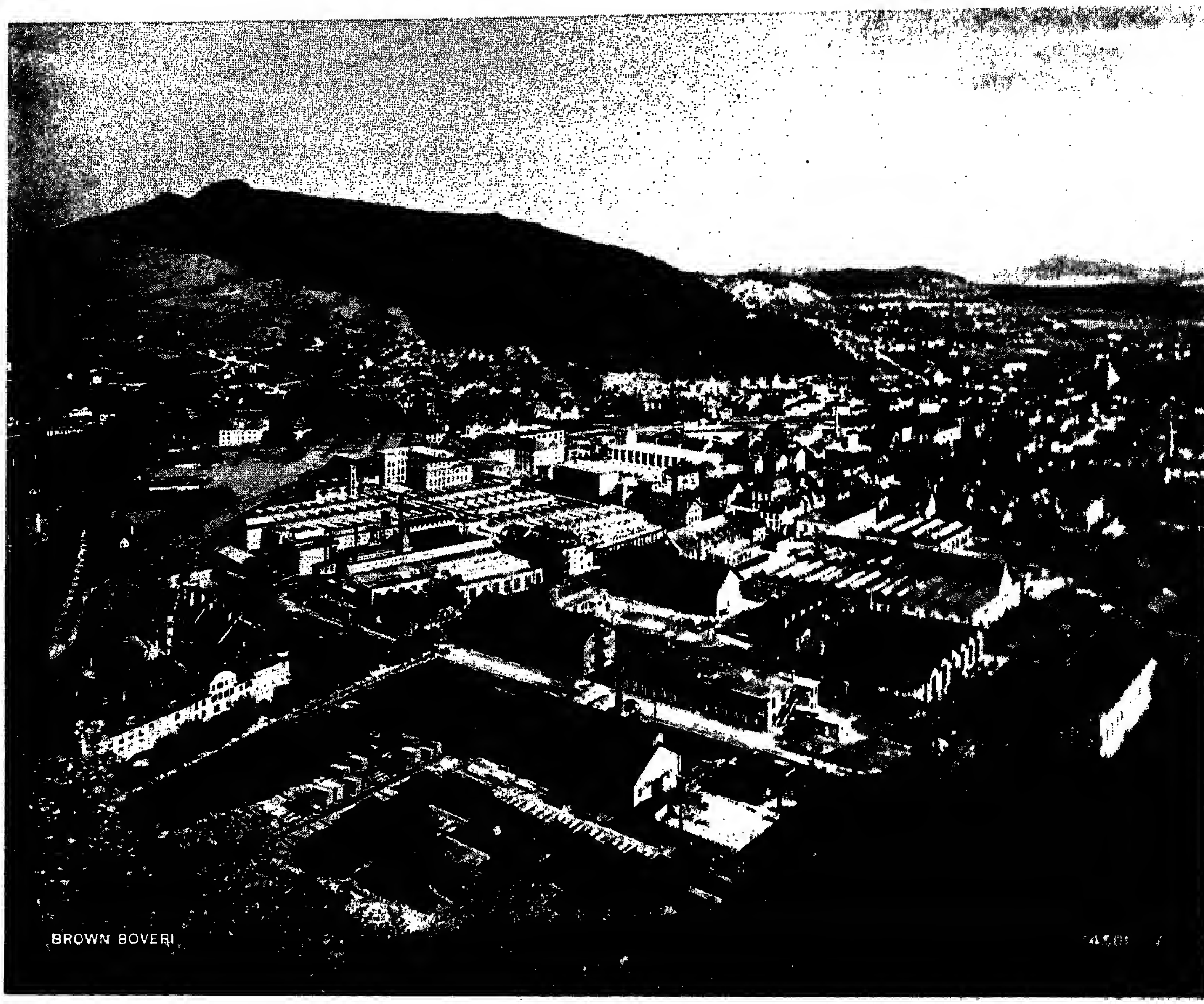
BROWN BOVERI

ALTERNATORS FOR HYDRO-ELECTRIC POWER STATIONS

BROWN, BOVERI & COMPANY
LIMITED
BADEN (SWITZERLAND)

854 E — II . 2
(2444)

February, 1926



General view of the Baden Works of Brown, Boveri & Co. (Switzerland).

CONTENTS

BROWN BOVERI
ALTERNATORS FOR HYDRO-ELECTRIC POWER STATIONS

INTRODUCTION

In no branch of machine construction has more progress been made or a greater variety of types been developed than in the building of water turbines.

Endeavours towards independence of foreign fuel supplies and the necessity for the greatest economy have resulted in the utilisation of all natural resources, particularly water power, to an altogether unexpected degree; power stations of ever increasing size are springing up on all the swift rivers, and in many countries the energy of mountain streams, hitherto wasted, is now being made available for power purposes by the employment of natural or artificial lakes as storage reservoirs.

In striving to minimise the capital outlay for power stations, the tendency is always towards larger units and higher speeds, and naturally, the construction of alternators has to keep pace with this progress.

Fig. 1. Open type three-phase alternator.

When Brown, Boveri & Co. was founded in the year 1891, the development of water power was just beginning, and from the very first the firm has devoted the greatest attention to this question. It has always been in a position to produce alternators fully up to the standard demanded by the progress in turbine construction, ample proof for which is furnished by numerous generating sets in many lands.

Brown Boveri alternators for coupling to water turbines are rotating-field machines, i.e., the rotor carrying the magnet poles on its outer circumference revolves within the laminated stator provided with the alternating-current winding. They are grouped into three main classes according to the degree of protection.

PROTECTION

1. Open machines in which the cooling air is perfectly free to flow to and from the current-carrying parts, are illustrated in Figs. 1 and 2. This type has the advantage of accessibility, and is employed for slow-running machines (flywheel alternators) and also for machines of small output at medium speeds.

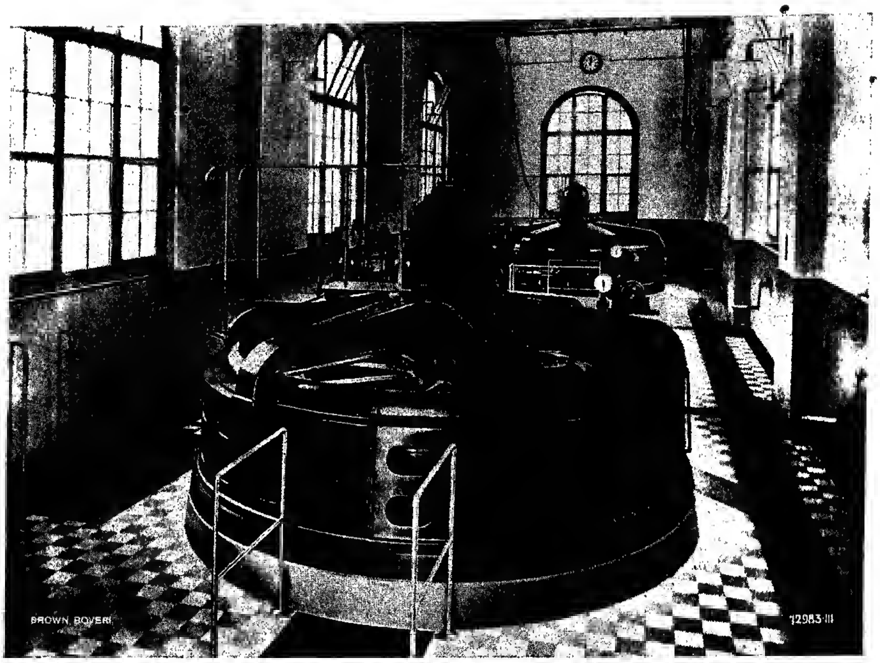


Fig. 2.
Open three-phase alternators, each 220 kVA, 2100 V, 50 cycles, 150 r. p. m. in the power station of the Wettingen Spinning and Weaving Mills, Wettingen, Switzerland.

2. **Protected machines,** which are cooled by air which is drawn from the neighbourhood of the machine and after traversing definite paths is discharged again into the open. The design of the frame and casing is such as to eliminate practically all risk of accidental or careless contact with live or moving parts. To this class belong the high-speed machines of small and medium outputs (Figs. 3 and 4), including those provided with end shields (Fig. 5).
3. **Enclosed machines** (Figs. 6 and 7), in which all live and rotating parts are completely enclosed, and suitable inlet and outlet openings connecting with the air channels are provided for the cooling air. This type of construction is always employed for large high-speed machines, with which, on account of the great volume of cooling air necessary, it is essential to keep this

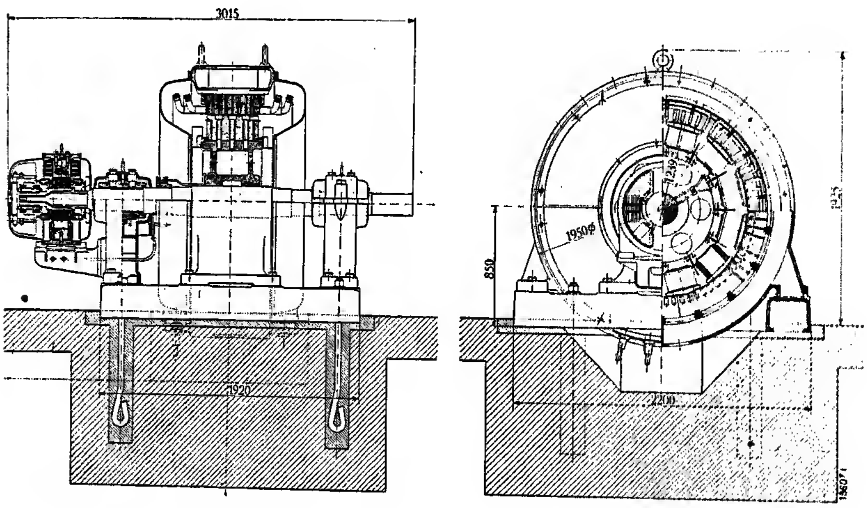
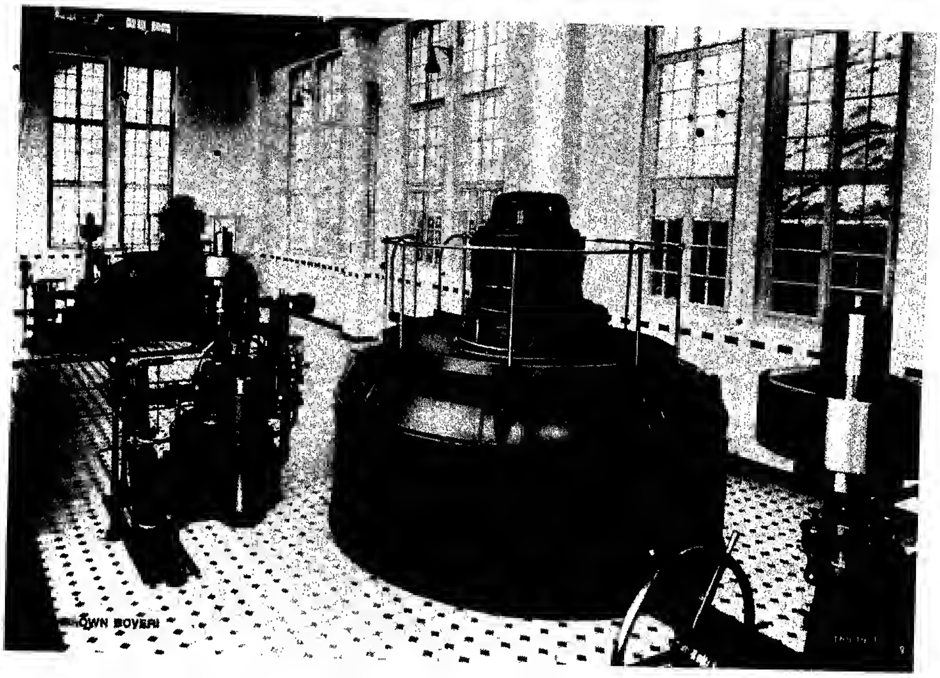


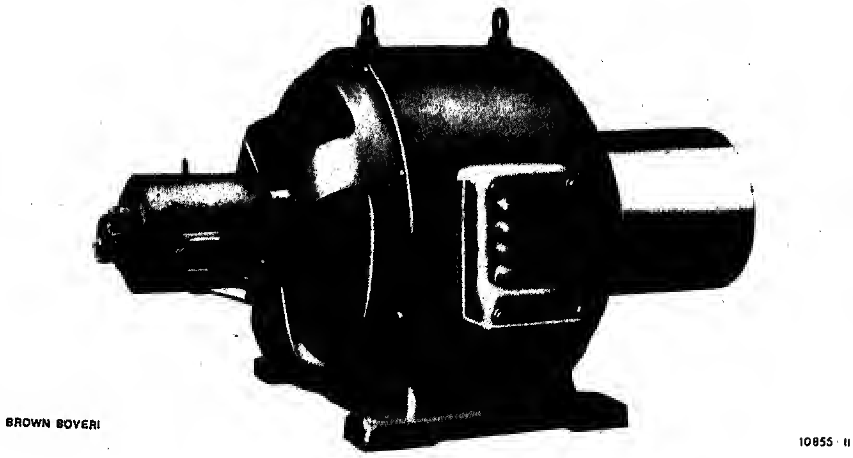
Fig. 3.
Section through a protected three-phase alternator.

Fig. 4.
Protected three-phase alternators, each 1390 kVA, 10,500 V, 50 cycles, 300 r. p. m.
at the Ziegenruck plant of Carl Zeiss, Jena.



from the machine room. In this way, the draught so unpleasant for the attendants, can be eliminated, and the noise of the machine minimised. A further advantage of enclosed machines is that the temperature of the machine room is under control, the whole of the warm air from the machines being discharged into the open during warm weather, while in winter it can be used for heating the machine room or other portions of the power station such as the switch house. The air channels are usually formed in the concrete foundations, control valves or shutters being provided where necessary, either when the warm air is used for heating purposes as described above, or to ensure a correct distribution of air when a number of machines are supplied from a common channel.

Fig. 5.
Three-phase alternator end-shield pattern.



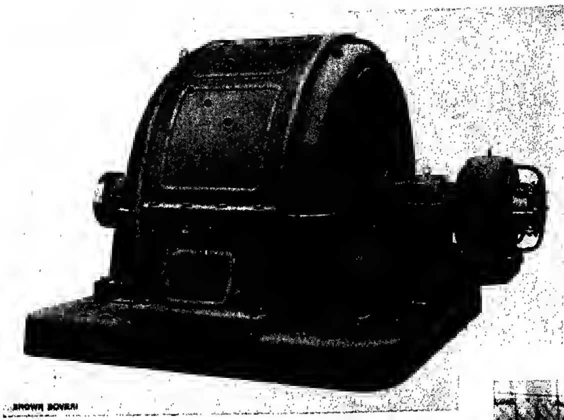


Fig. 6.

Fig. 6. Enclosed three-phase alternator.
Two alternators, each 4000 kVA, 8400 V,
50 cycles, 750 r. p. m.,
installed in the Lungern Power Station of the Central Switzerland Supply Co. at Lucerne. A similar alternator for 12,000 kVA has since been supplied.

Fig. 7. Enclosed three-phase alternator. Three alternators, each 3000 kVA, 5000 V, 50 cycles,
750 r. p. m.,
are installed in the Buitreras Power Station of the Soc. Hidro-Electrica del Guadiaro (Spain).

Fig. 8. Enclosed single-phase alternators in the Ritom Power Station of the Swiss Federal Railways,
each 9000—11,500 kVA, 15,000 V,
$16^2/_3$ cycles, 333 r. p. m.

In all four alternators have been delivered; see also Fig. 94.

Fig. 9. Protected three-phase alternator.

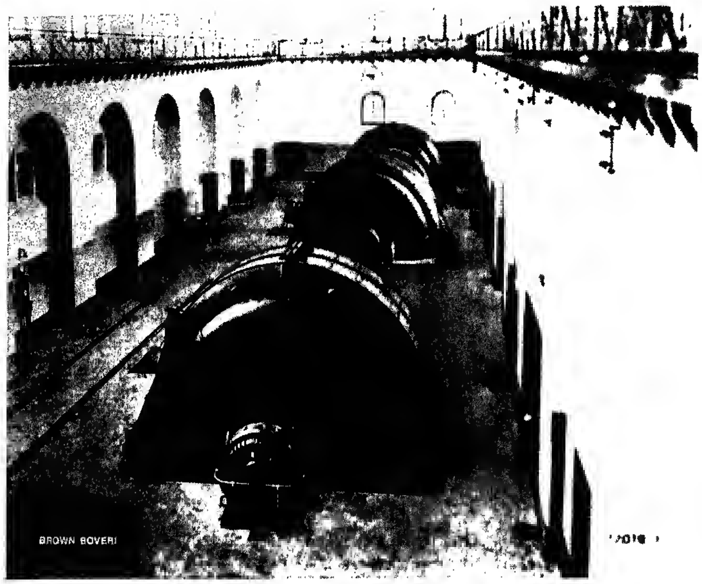


Fig. 8.

Fig. 7.

Fig. 9.

COOLING

Brown Boveri alternators are air cooled, the two following methods being employed:

1. **Natural cooling** in which the motion of the air takes place without the use of any special equipment, solely as a result of the rotating parts of the machine itself. This method is only used for slow-speed machines of large diameter (flywheel alternators).
2. **Self ventilation** in which the air is drawn through the machine by fans fitted to its rotor (Fig. 3). Most Brown Boveri machines are self-ventilating, particularly those of the protected and enclosed types.

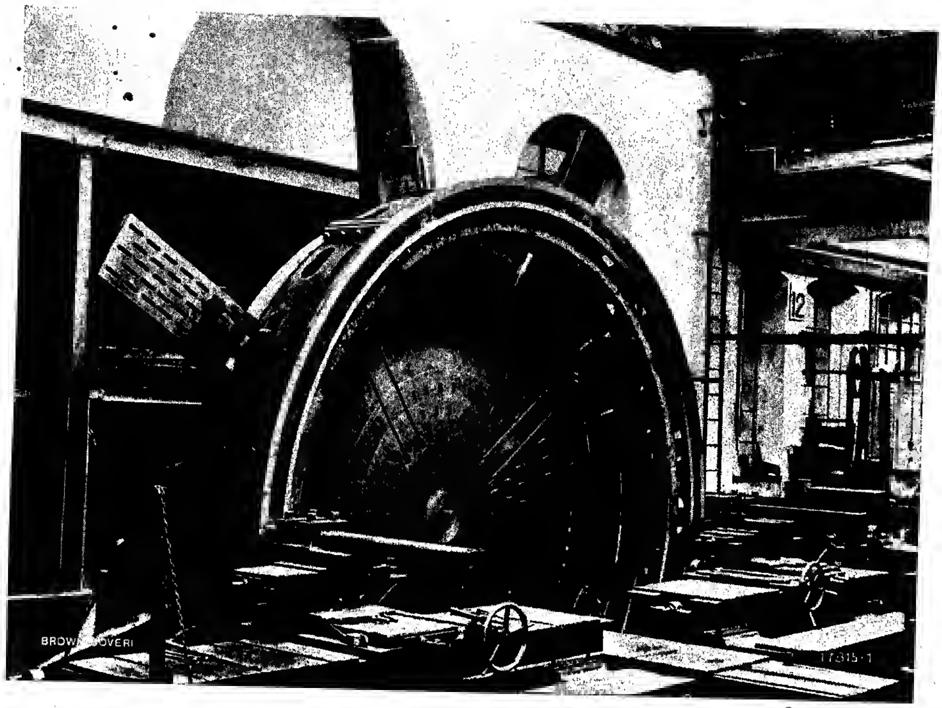


Fig. 10. Machining a stator for a three-phase alternator, 2200 kVA, 9500 V, 50 cycles, 107 r. p. m.
Four similar machines have been supplied for the Wynau Power Station of the Wynau-Langenthal Power Supply Co.

All that has been said regarding protection and cooling applies equally to machines with horizontal and vertical shafts. The following sections deal more fully with the various details of alternator construction.

THE STATOR FRAME

In designing the stator frame, care is taken that it is sufficiently strong to withstand, without deformation, both the weight of the machine and the magnetic forces when the machine is in operation. The frame is of cast iron and its details naturally depend upon the extent of the protection.

The frame of an open machine is usually provided with openings round the whole circumference to serve as outlets for the cooling air (Figs. 1 and 2).

With protected machines (Figs. 3, 4, and 9), the frame is designed to serve as a discharge duct for the cooling air and has openings in its upper part only for air outlets.

In order to save weight, larger machines have openings round their whole circumference, except for those required as air outlets. The frame of enclosed machines are similarly constructed (Figs. 6 and 7).

Every frame is provided with two flanges, one of which can be cast on, and between which the laminations are compressed. The laminations are held in position by means of laths of trapezoidal section screwed to the interior of the frame. In machines of small axial length, particularly those of the open type, these laths are replaced by round bolts over which the laminations are slipped.

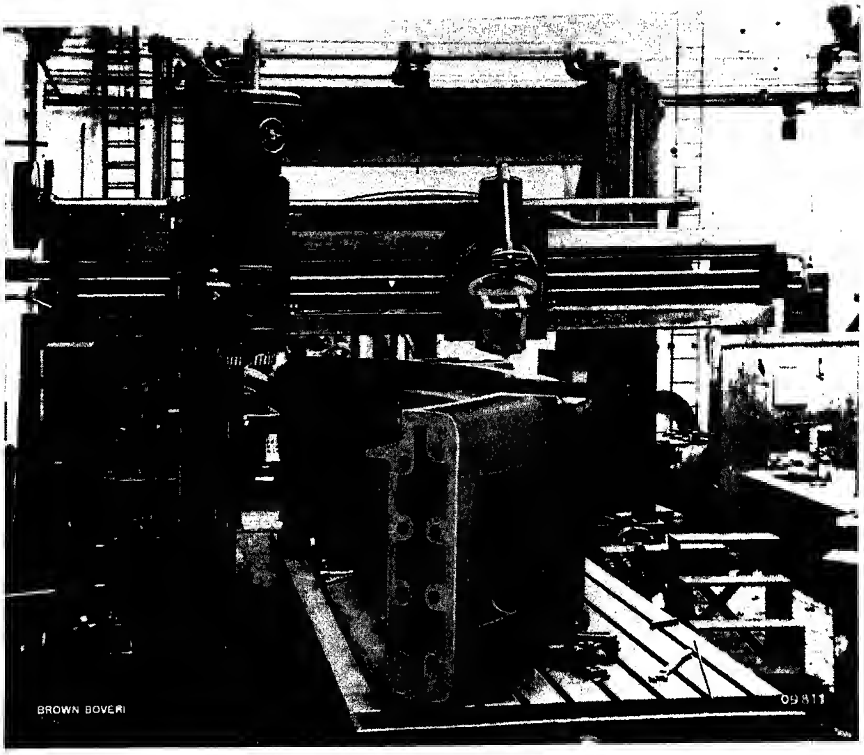


Fig. 11. Machining a section of the stator frame of an alternator, 7050 kVA, 83·3 r. p. m.,
for the Gösgen Power Station of the Olten-Aarburg Electricity Supply Co., see also Fig. 89.

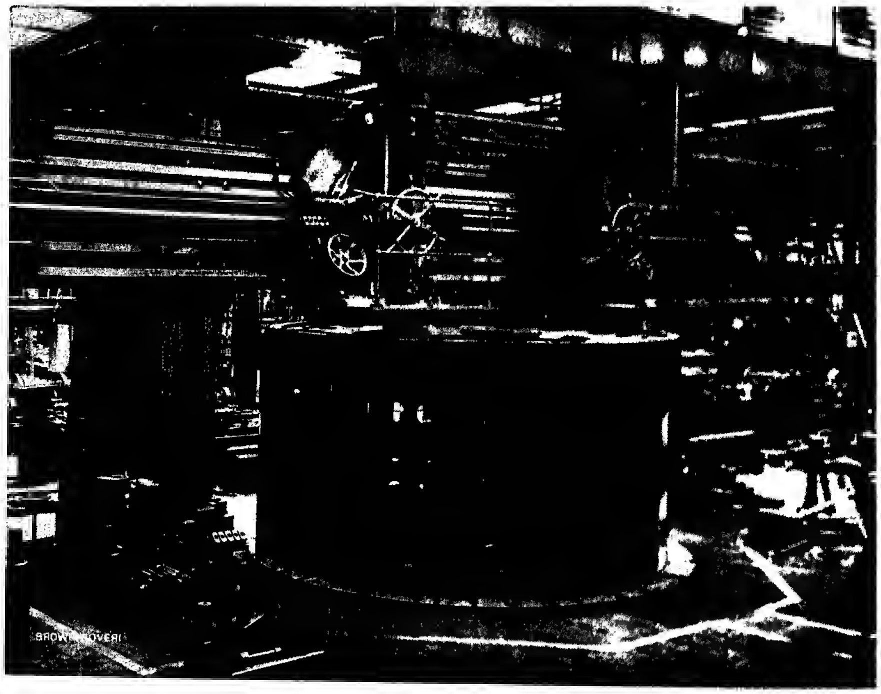


Fig. 11 a. Machining a large stator on the turning and boring mill.

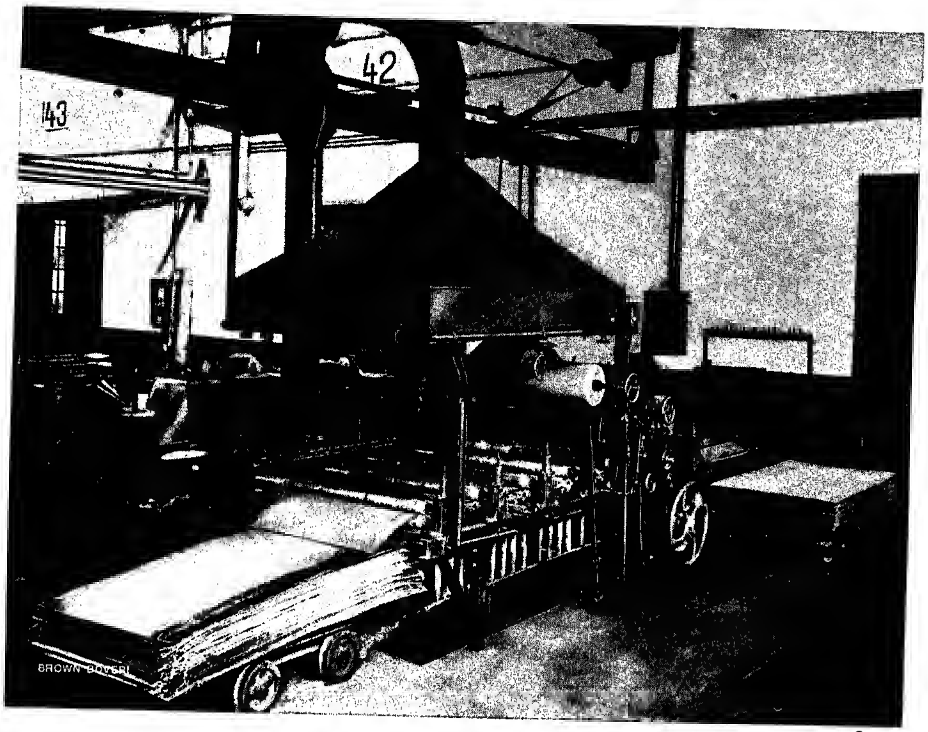


Fig. 12. Machine for pasting paper insulation to dynamo-steel sheets.

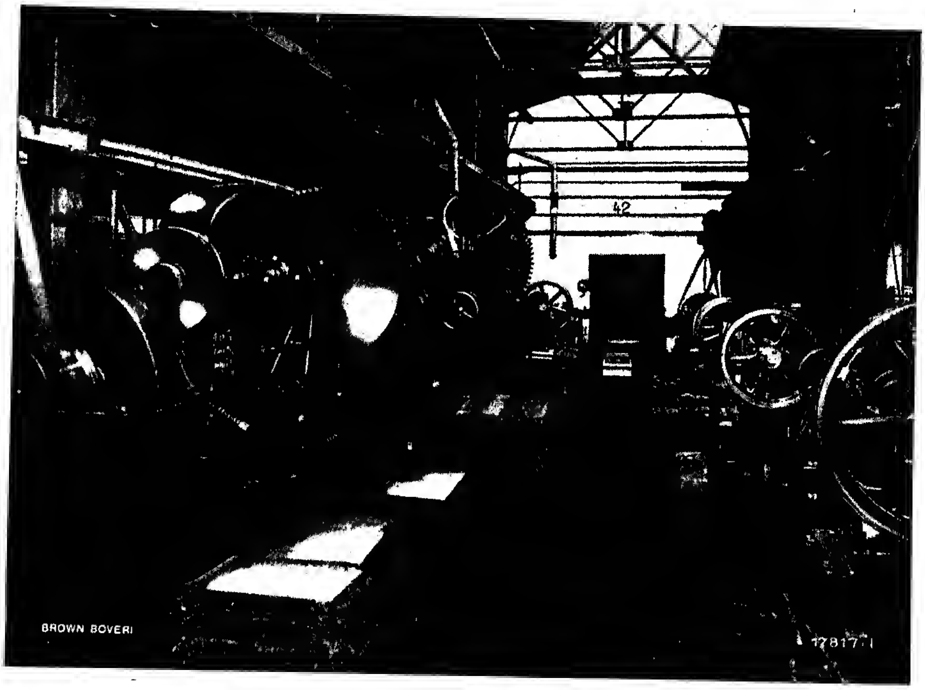


Fig. 13. A bay where the sheets are stamped to size and slotted.

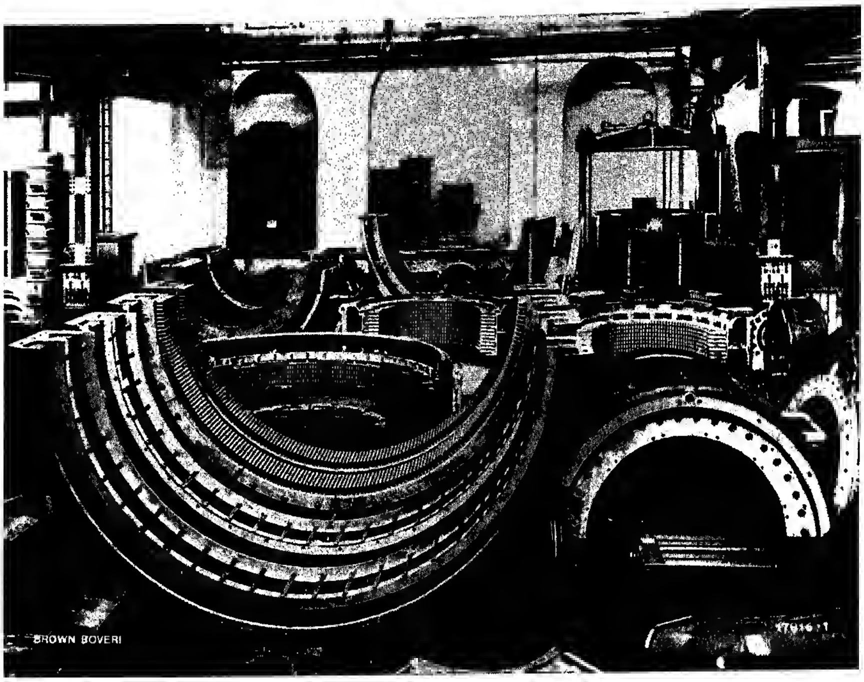


Fig. 14. A bay where the laminations are placed in the stator.

The main part of the stator is built up of lamination segments stamped out of dynamo sheeting 0·5 mm in thickness and faced on one side with thin paper. In the process of building up, successive layers are displaced with regard to eachother, and distance pieces are inserted at suitable intervals to provide a free passage for the cooling air.

The inside of the laminated core is provided with winding slots which are half open, or open, according to the type of winding adopted. The teeth between the slots are firmly supported by T-section steel fingers welded to end plates somewhat heavier than the laminations themselves; this effectively prevents any vibration of the latter.

As far as considerations of weight and space for transport allow, the whole stator is built in one piece, i.e., up to a weight of about 10—15 tons and an outside diameter of 2·8 m. For weights and dimensions exceeding these, the stator is as a rule constructed in two portions. For unusually large machines it is sometimes found necessary to go still further and divide the stator into three or even four parts.

The stator of a horizontal-shaft alternator is provided with two heavy feet which rest on the bedplate or soleplates. In certain cases these feet are made removable (Fig. 15), so that after the feet are removed, the stator rests upon the rotor, with which it can be revolved. When space is very limited and the lower portion of the stator would otherwise be inaccessible, this feature is often a great advantage, as the lower part of the stator can be turned upwards until it is in a position where inspection or repair is possible. This arrangement is not always practicable and is only employed by Brown, Boveri & Co. when there is no alternative. It is only applicable to machines with a relatively light stator and therefore of small axial length. The stators of heavy machines are provided with turned rims on the outer circumference for the same purpose; these run on rollers situated in the pit (Fig. 16). The latter arrangement is adopted for high-power alternators, particularly when they are wound for high voltages.

The stator of vertical-shaft generators rests either upon a circular bedplate or upon a number of sole plates.

THE STATOR WINDING

The most important part of an alternator is the stator winding and it demands the greatest care on the part of the designer. Various methods of winding are employed according to the requirements, particularly as regards voltage. From the point of view of design, stator windings

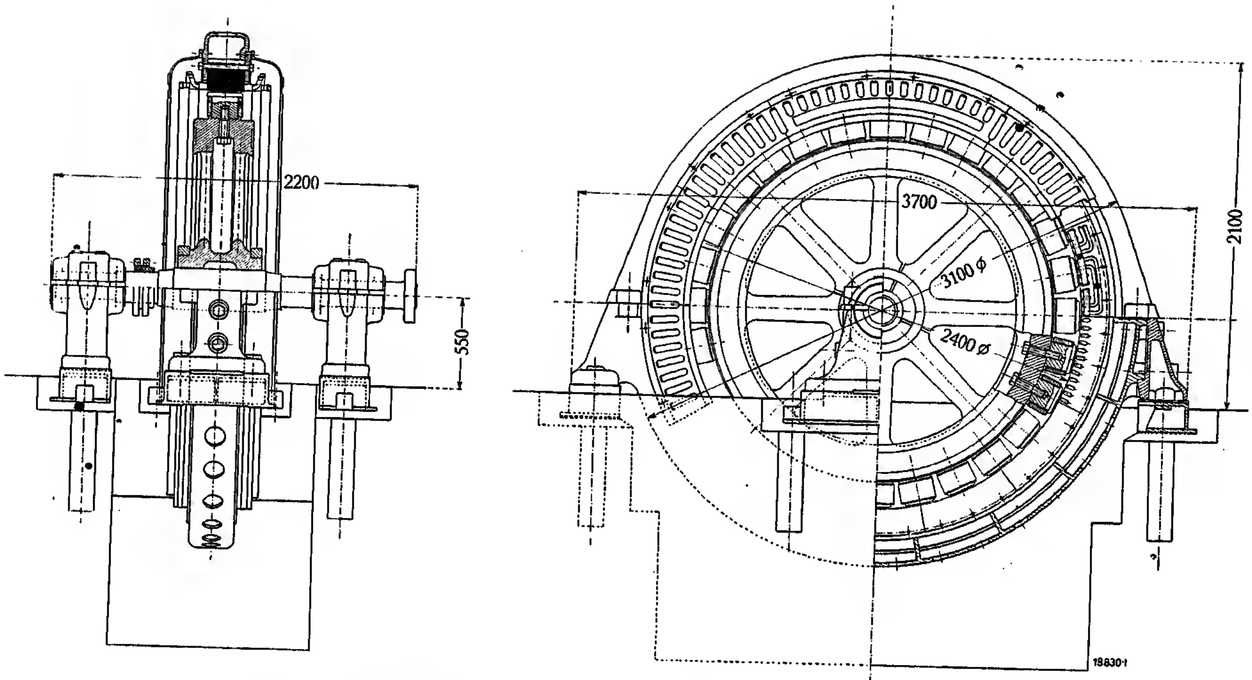


Fig. 15. Section through a three-phase alternator with removable stools, 650 kVA, 3000 V, 50 cycles, 215 r. p. m.

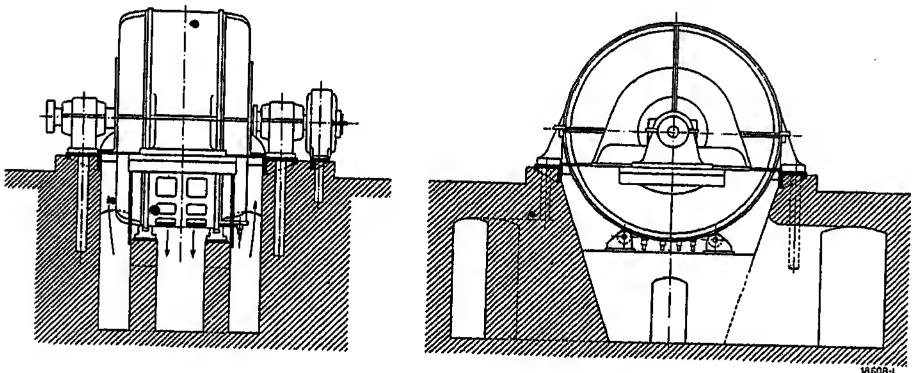


Fig. 16. Three-phase alternator with movable stator.

are divided into two classes: coil winding and bar windings. They are considered to be of the latter type when each slot contains only one or two turns or bars, each bar being insulated for the full voltage. *Bar winding* is only employed when the current is 600—1000 A or more.

When the cross section of the bar exceeds about 300—400 mm², it is important to take care that the eddy-current losses resulting from the skin effect are prevented as much as possible. This is effected by employing the Brown Boveri twisted-strand type of stator winding (Fig. 17), in which the bars are built up of a number of strips and transposed so that each strand occupies every possible position in the cross section of the slot in turn. The individual strips are insulated from each other by alternate layers of paper. This is the most satisfactory form of bar winding which has yet been evolved, and has the advantage of simplicity and a good appearance. The ends of the stranded bars

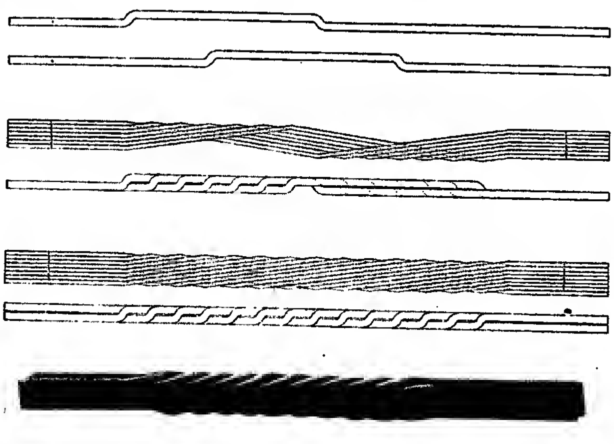


Fig. 17. Brown Boveri bar winding for heavy currents.

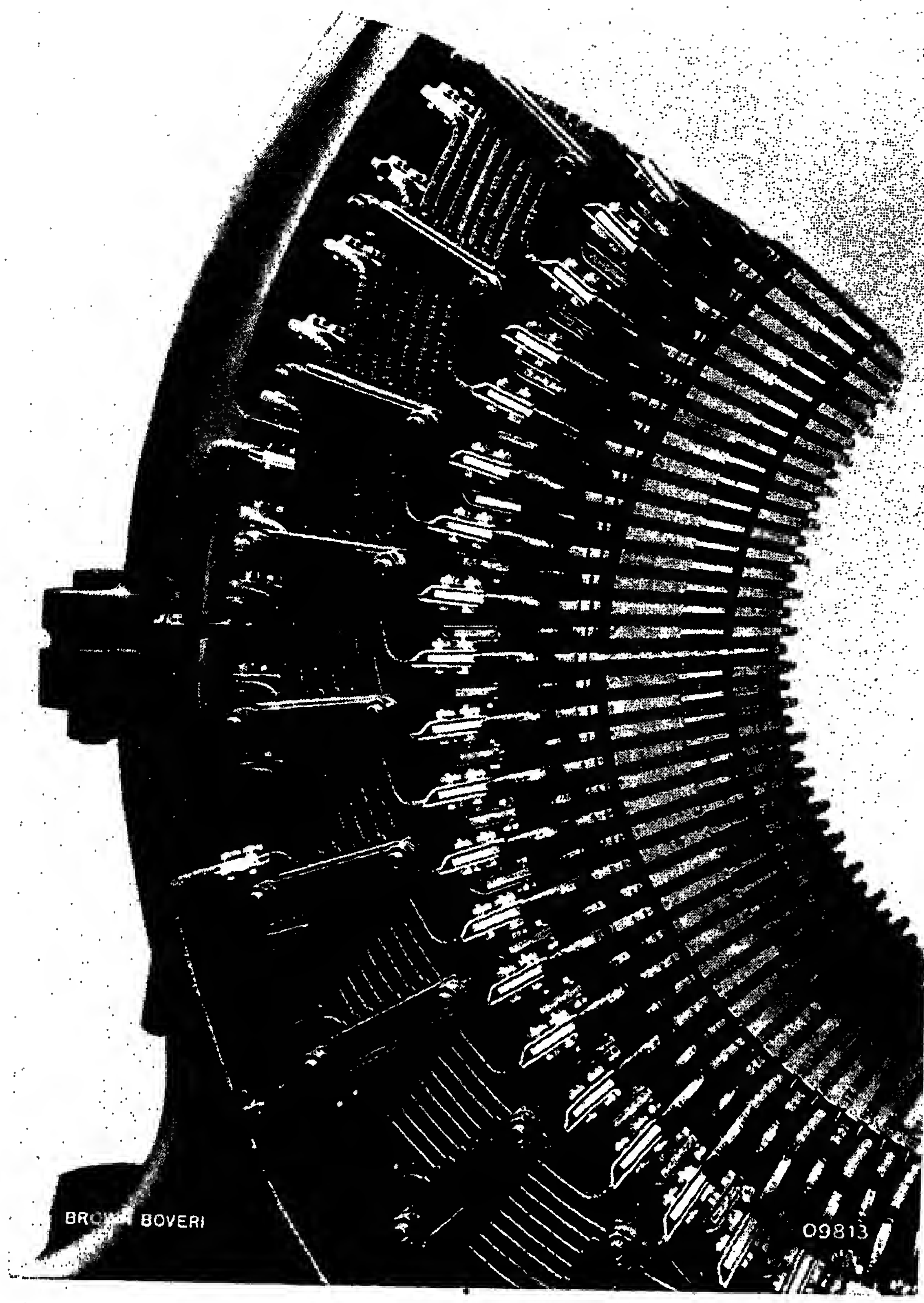


Fig. 18. Bar winding for 5750 V.

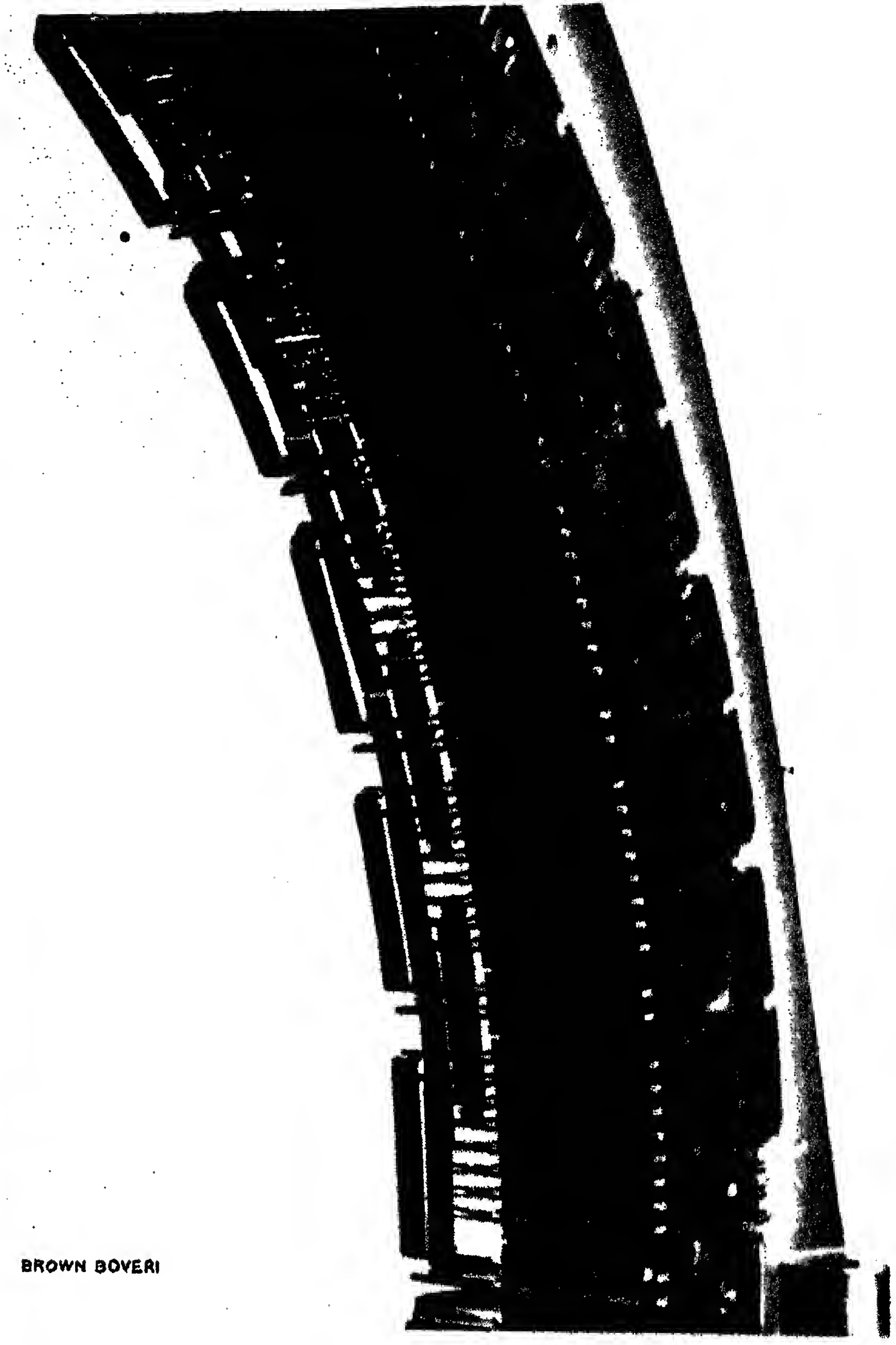


Fig. 19. Bar winding for 525 V.

are soldered and provided with a cap of sheet copper, and the end connections are made with massive curved strips of copper, so that a winding of this kind possesses considerable mechanical strength. The joints between the bars and the end connections are made by bolting (Fig. 18), soldering (Fig. 19), or riveting, according to the conditions in each individual case. Each bar is insulated with a sheath of micanite. The insulation of the end connections is carried out by binding with mica cloth, varnished tape, or a combination of both according to conditions.

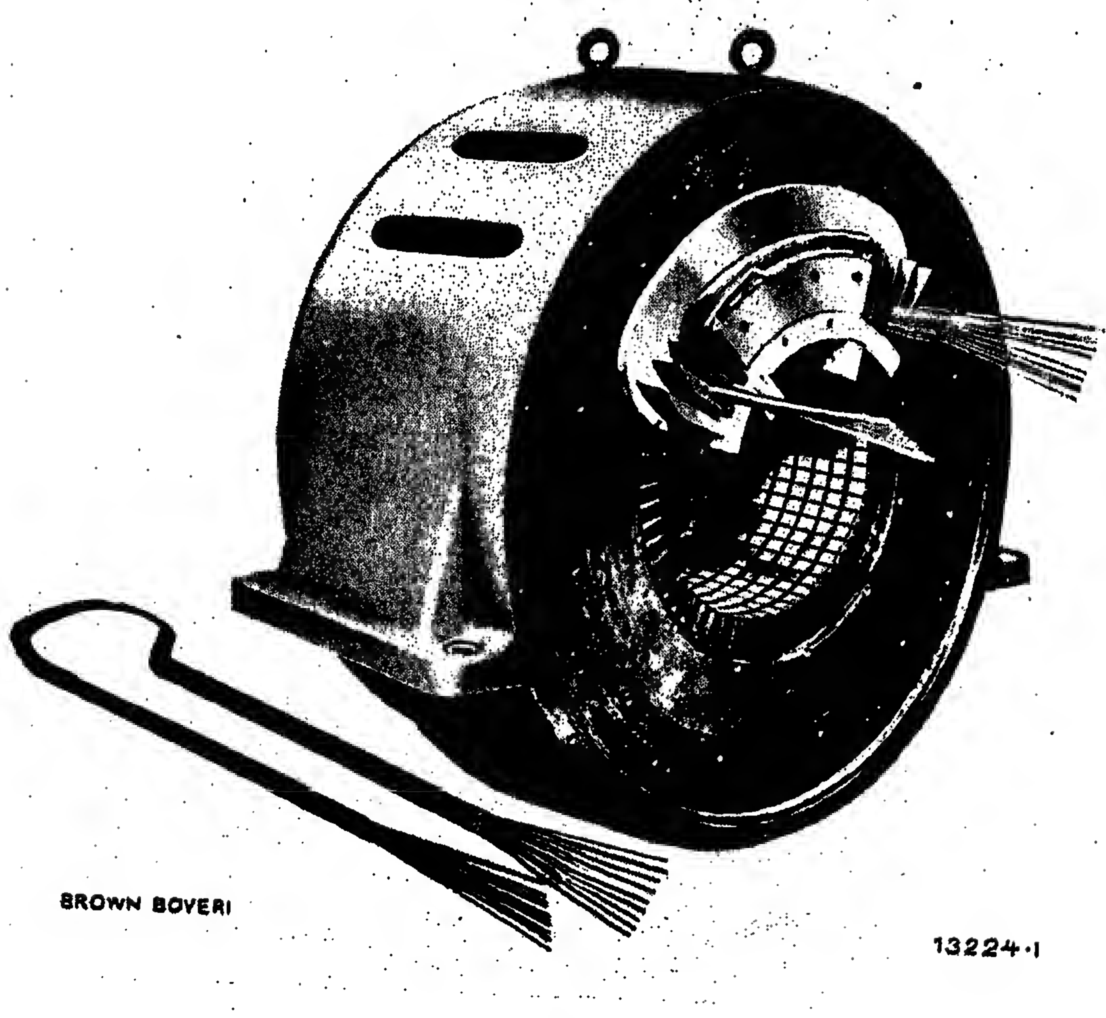


Fig. 20. One end of a 5000-V former winding, opened.

Bar windings are usually placed in half-open slots. The bars have therefore to be pushed into position from the end and also removed in a similar manner should replacement be necessary. This may give rise to difficulties as the micanite sheath tends to expand after the machine has been in operation some time, gripping the sides of the slot, so that withdrawal of the old bar wastes a great deal of time. The best solution of this difficulty is to use slots of the form illustrated in Fig. 21; by use of suitable

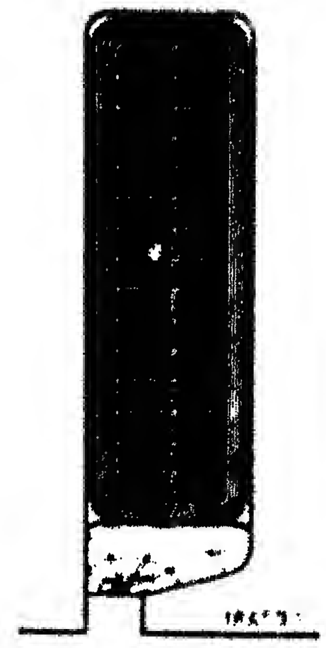


Fig. 21. Section through a bar winding.

instruments applied through the slot opening, the insulation can be loosened on one side and if necessary removed altogether, after which the bar can easily be withdrawn.

The application of the bar winding is naturally somewhat limited, but that of *coil winding* is considerably wider; it is employed whenever bar winding is unsuitable, particularly for high voltages. In this connection, Brown, Boveri & Co. have had extensive experience; they have the distinction of being the first firm to undertake the construction of high-tension generators, and at a time when the materials and methods of insulation which are to-day in general use were unknown.

Brown, Boveri & Co. employ various forms of coil winding which may be classified as follows:—

1. **Hand winding.** The half-open slots are lined with seamless insulating tubes of micanite, through which the winding, usually of insulated and impregnated wire of circular section, is drawn by hand. In order to protect the insulation of the wire when pulling it through, the layers are separated by thin strips of presspahn. The coil ends are taped with varnished tape. Hand winding is employed for machines of small and medium output and pressures up to about 5000—6000 V, for which purpose it has proved entirely satisfactory.

2. **Former-wound coils open at one end.** This method of winding is also suitable for half-open slots. The coils are wound on formers and fully insulated and impregnated, the straight portions being sheathed in micanite and the closed coil end taped with varnished tape. The other end is left open, so that the coil can be slid into position in the slots, after which the free ends of the separate turns are bent round and either soldered or welded to each other. Winding of this kind is suitable for more powerful machines and for pressures up to 8000 and 10,000 V, where open slots cannot be used.

3. **Finished former-wound coils for sliding into position.** These coils are completely formed and insulated, and are also suitable for half-open slots, the opening being sufficiently wide to allow the coil end to pass as shown in Fig. 22, when the coil is slid into position like a drawer.

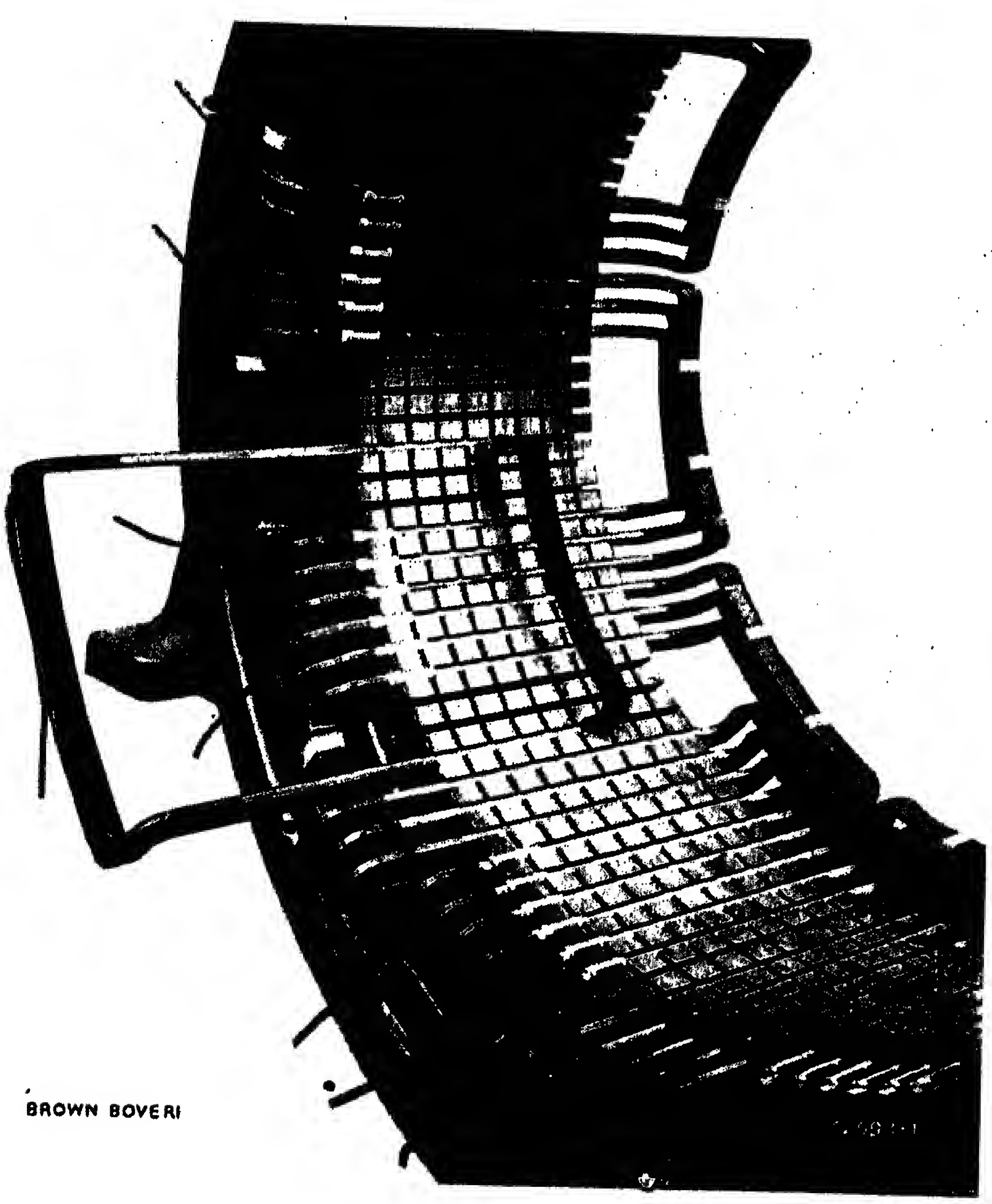


Fig. 22. Former-wound coils for 6000 V in position.

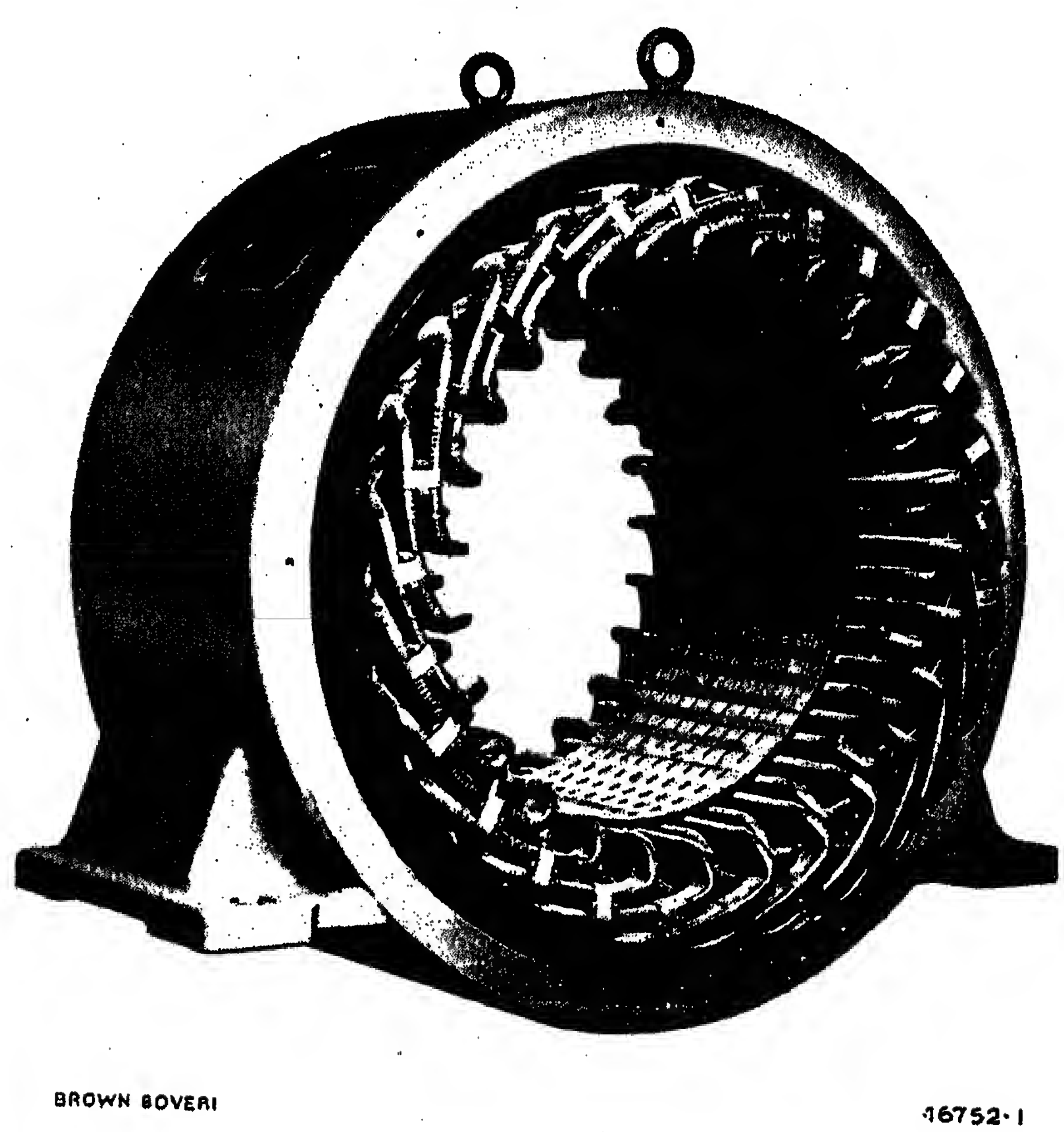


Fig. 23. Former-wound stator for 6300 V completed.

This type of winding is used for multipole machines up to about 8000 V.

4. **Former-wound coils for laying in position in open slots.** The completely wound and insulated coils are held in position in the open slots by means of impregnated hardwood wedges (Fig. 23 and 24). This type of winding is suitable for machines of large output and the highest pressures for which generators are constructed (up to 20,000 V).

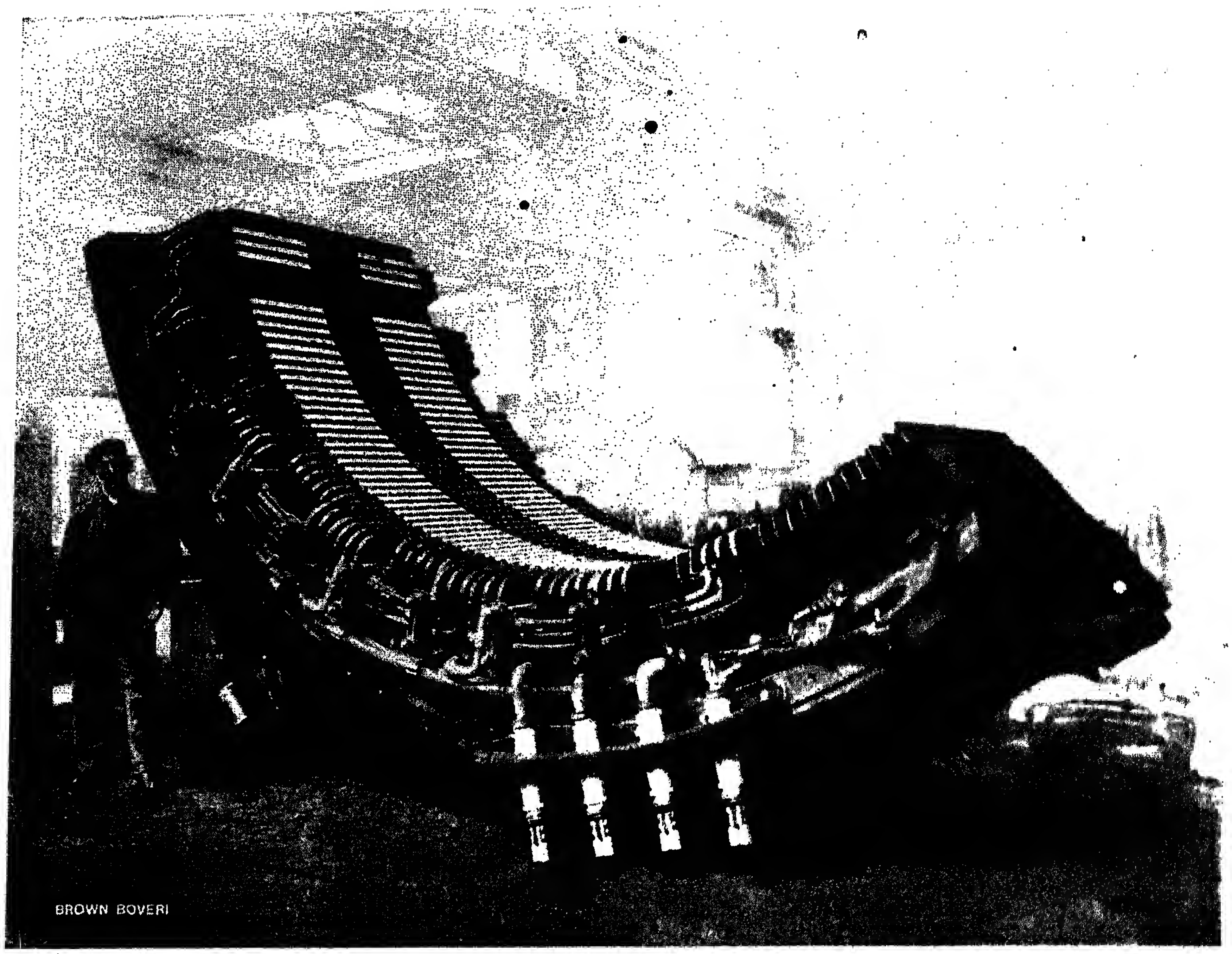


Fig. 24. Part of a completed former-wound stator for 10,500 V.

The manufacture of the former-wound coils, referred to in 2, 3 and 4 above, demands a great amount of care and considerable mechanical equipment. Conductors of small cross section consist of cotton-covered wire, but, apart from this, the coils are built up of bare copper, preferably only a single layer being employed so that the voltage between neighbouring turns is relatively small. When heavy currents have to be dealt with, each conductor is subdivided into a number of strands which are suitably crossed to minimise the eddy losses. These strands are separated from each other by thin layers of insulating material such as paper or mica. All the strands composing a conductor are then wrapped with mica cloth throughout the straight portions which lie in the stator iron; the end connections are wound with paper, cotton tape, or, in special cases, also with mica cloth. The conductors are separated by strips of mica paper or presspahn. The coils prepared in this way

Fig. 25. Impregnating plant for high-tension windings.

are ready for impregnation. After having been dried under vacuum, they are thoroughly saturated with an insulating compound at a temperature sufficiently high to convert it into a thin liquid, so that it penetrates all pores and empty spaces. This process completed, the coils pass to the presses where they are pressed between heated jaws to the accurate cross section desired, the superfluous insulating compound being forced out. The final layer of insulation is now applied; this consists of a micanite sheath on the straight portions and several wrappings of varnished tape on the coil heads. The former is made up of micafolium, — thin tough paper faced with flakes of mica, — many layers of which are wound on to the coil, the thickness being regulated according to the voltage; this is finally smoothed off in a machine with electrically heated irons. In this way, a micanite tube is formed completely enclosing the straight part of the coil, and it only remains to check the dimensions; the coil must fit the stator slots exactly, and, if necessary, it must be again subjected to pressure until the correct cross section is obtained. Before it is placed in position in the machine, each coil is subjected to an exacting insulation test, so that any defect in material or workmanship is detected and rectified, or the coil replaced. This test is repeated after the coil is in position in the stator.

The method of insulation described is the result of research and experience extending over many years and ensures the production of coils capable of fulfilling the strictest demands both electrically and mechanically. The impregnation process in particular prevents the ingress of all air and moisture, and in this way eliminates all danger of the formation of ozone, which, as is well known, can destroy the insulation in a very short time. The solidarity obtained by the impregnation and pressing processes prevents any tendency for the individual conductors to work loose and vibrate, which would also ultimately result in the destruction of the insulation.

If the test voltage is abnormally high (three times the rated voltage and over), particularly when one pole is earthed (traction alternators), it is inevitable that the dielectric strength of the slight air spaces remaining between the coil insulation and the slots will be overstressed while the pressure test is being carried out and will consequently be the source of discharge effects. To remedy this, the insulating sheath of the coil is provided with a coat of conducting varnish, shunting the air space between coil insulation and stator iron. The conditions are particularly difficult in the case of 15-kW single-phase traction alternators, which necessarily work with one pole earthed. Here, on account of the unfavourable flux distribution, silent and brush discharges endangering the coil insulation are very liable to occur at the edges and corners of the teeth and clamping plates in the neighbourhood of the points where the high-tension conductors leave the iron. In order to prevent this, the coils of Brown Boveri machines of this type are provided, at the points where they leave the core (Fig. 26), with a narrow conducting sheath c of tin foil, over which a sleeve of conducting material (brass) is drawn. Due to the connections thus made between the iron core and the sleeve, the surface of the coil at this point is artificially brought to the potential of the core, i. e., to earth potential, so that all discharge phenomena from the coil are now directed to the edge of the conducting sleeve d. Such phenomena can be easily and effectively done away with, by covering this edge with a layer of insulating material after the edge has been rounded off.

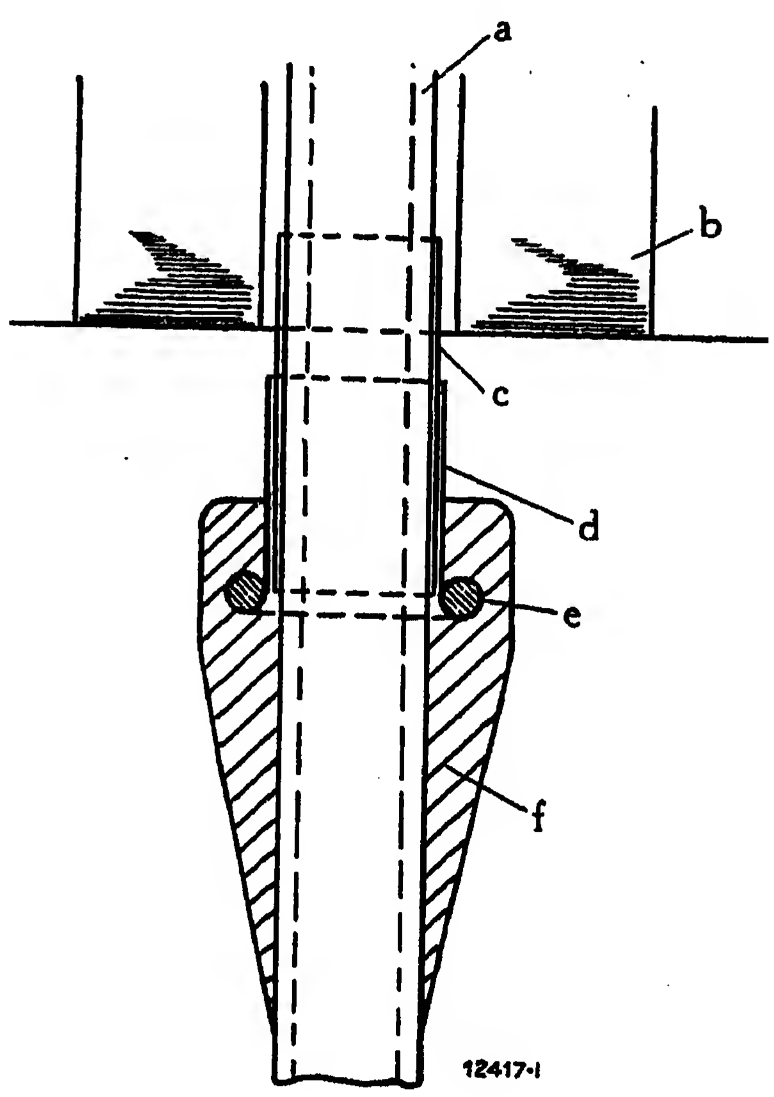


Fig. 26. Corona effect protection, as used on high-tension alternators.

A considerable number of Brown Boveri machines for pressures of 15,000—17,000 V have been in operation for as much as 15 years without any important disturbance or breakdown occurring; these alternators furnish ample proof that when the output is not too small, it is possible to construct machines on the above lines for

rated pressures up to 20,000 V, the reliability of which is not at all inferior to those working at lower voltages.

As an example, the Bernese Power Supply Company may be quoted, to whom a number of 16,000-V alternators were supplied as early as 1909. Since that time they have equipped their other power stations with machines for 16,000 to 17,600 V, making altogether 24 alternators with a total output of about 110,000 kVA. A further example is furnished by the power stations of the Swiss Federal Railways among which Ritom Station has been in operation many years and contains four 11,500 kVA alternators for 15,000 to 16,500 V, the other stations being also equipped with high-tension alternators.

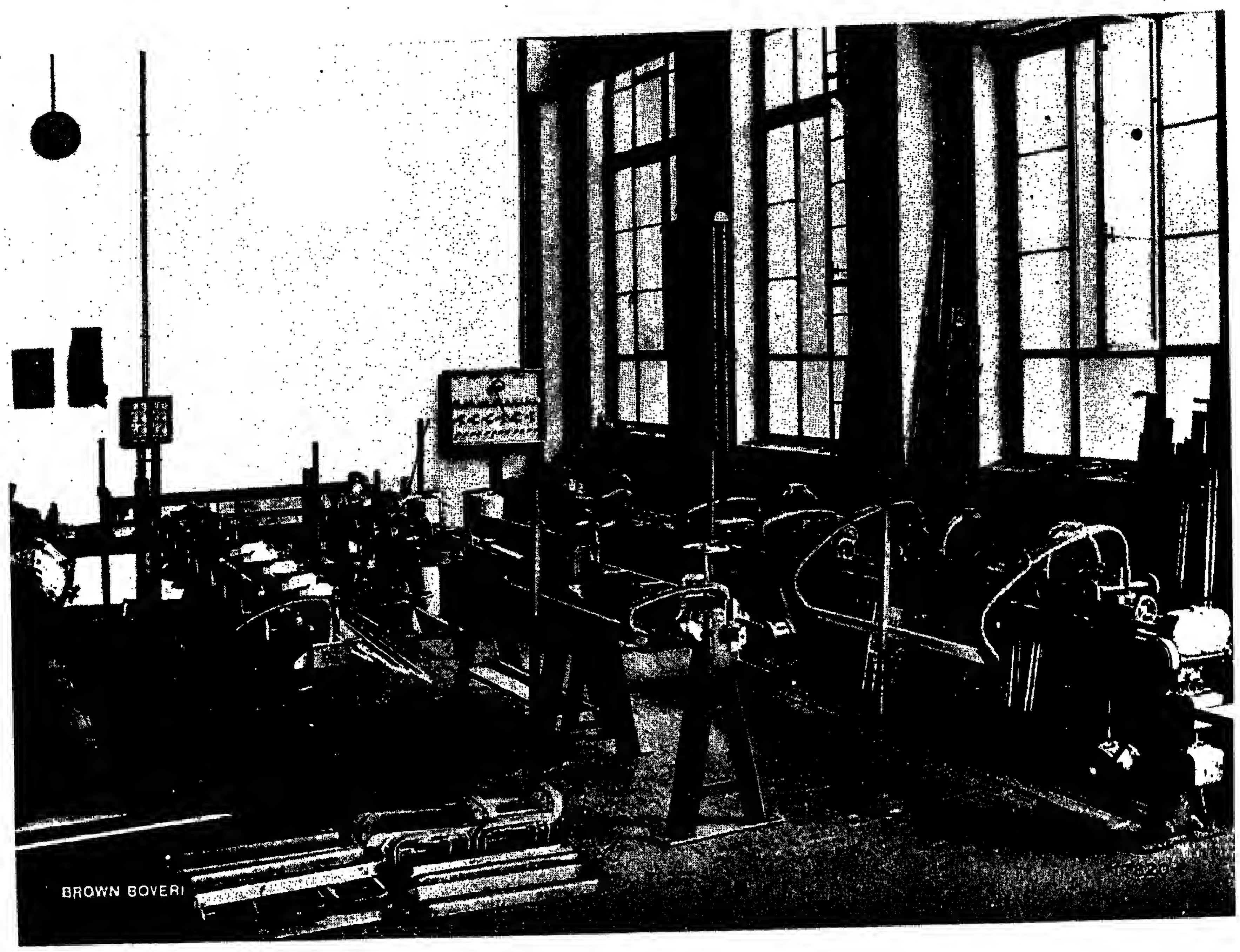


Fig. 27. Machines for sheathing the high-tension windings with micanite.

PROTECTION AGAINST SHORT CIRCUITS.

The momentary rush of current in the neighbourhood of the alternator terminals on sudden

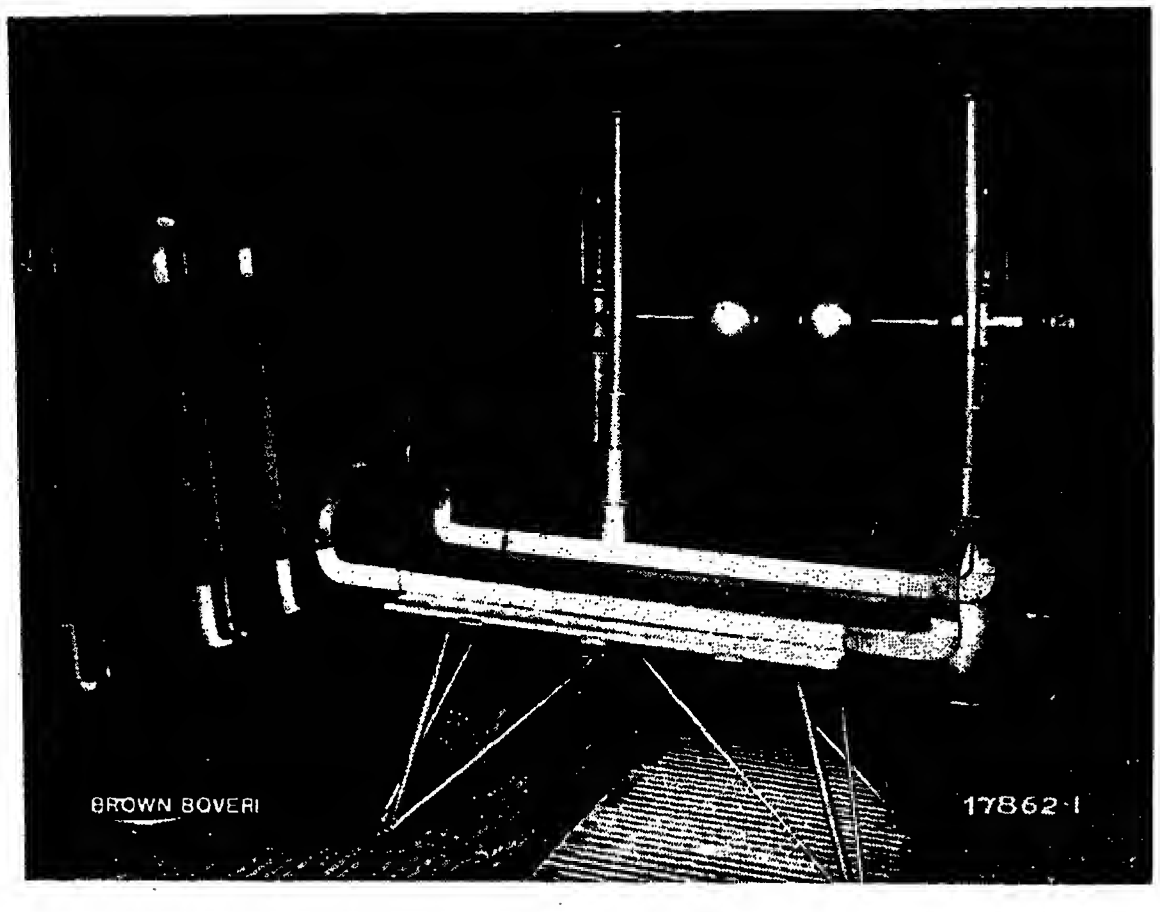


Fig. 28. Testing high-tension coils.

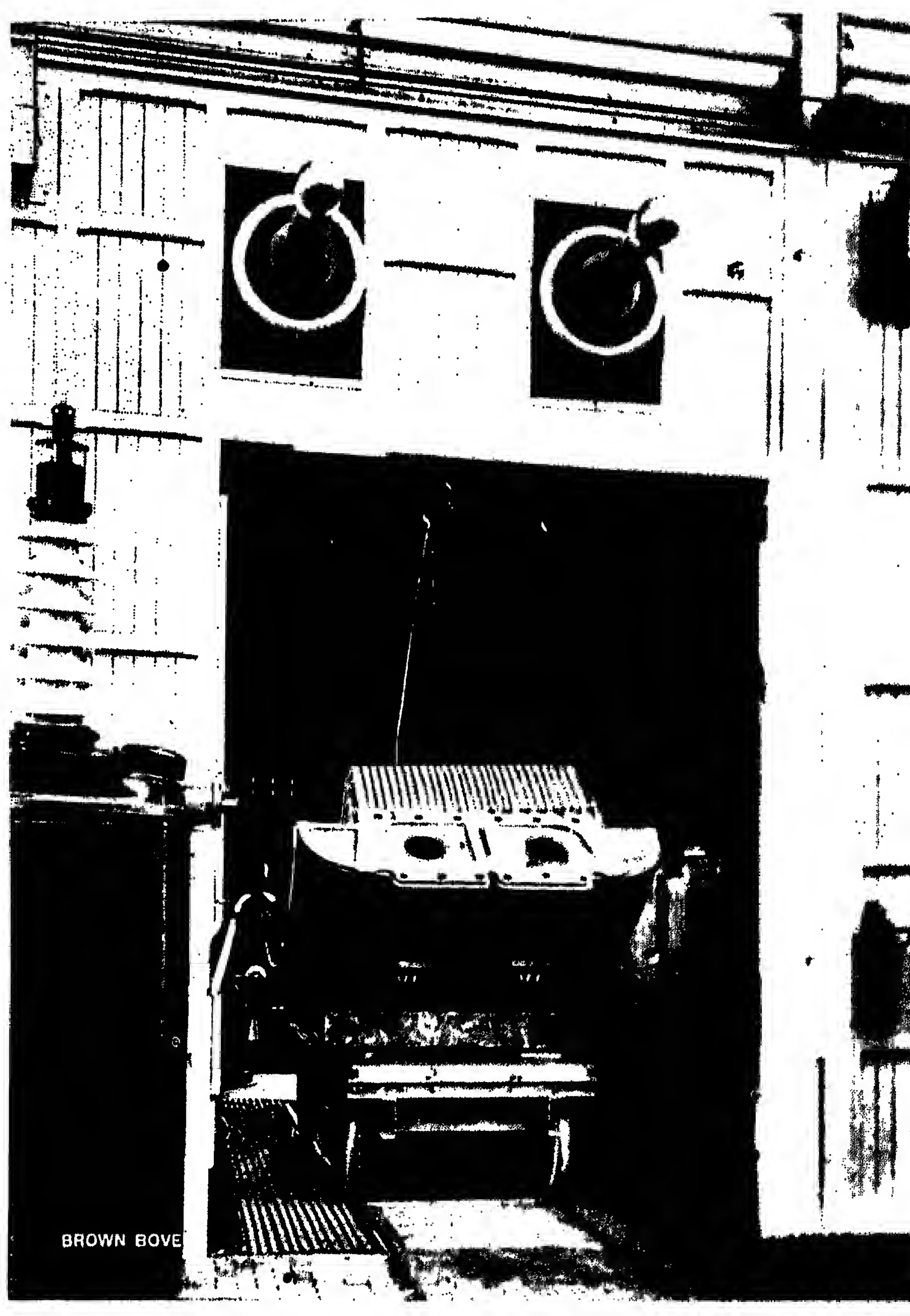


Fig. 29. Testing portion of an alternator stator.

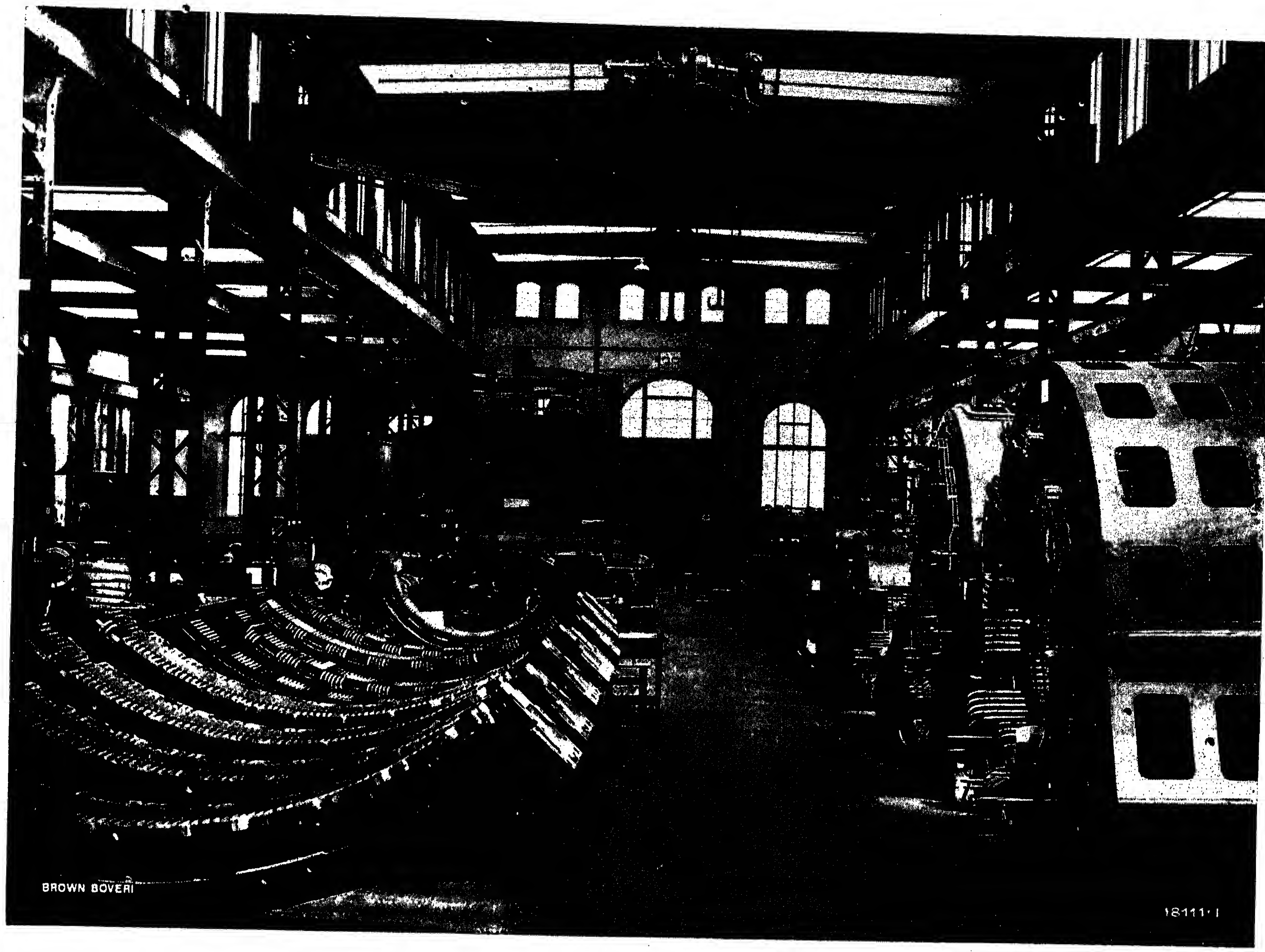


Fig. 30. A bay in the alternator winding shop.

short circuit can amount to as much as 15 times the maximum rated current. As the forces acting on the end connection increase as the square of the current, it can easily be seen that in the event of short circuit, these forces will become very considerable, and will tend to cause deformation which would result in weakening and ultimate breakdown of the insulation if repeated at all frequently. This difficulty is encountered particularly with high-power machines in which the number of poles is small, as the length of the end connection is relatively great in this case. It is consequently most important to support these lengths in such a way that they are able to

Fig. 31. Six three-phase alternators, each 8000 kVA, 17,600 V, 40/50 cycles, 133/167 r. p. m., in the Mühleberg Central Station of the Bernese Power Supply Co.

withstand the short-circuit forces. The magnitude and direction of these forces were determined both theoretically and by practical experiment and the hang-out support arranged accordingly. A system of bolts and brackets in conjunction with tubes and blocks of insulating material supports the coil heads against each other and against the frame as shown in Figs. 18 and 24. Care must naturally be exercised not to interfere in any way whatsoever with the flow of cooling air round the end connections.

TEMPERATURE MEASUREMENT

The extent to which an electric generator can be loaded is mainly determined by the temperature of its various parts, which must not increase sufficiently to damage the insulating materials employed. All temperatures must be kept within the limits specified in national and international standard rules, and it is therefore necessary to measure the temperature occurring at various points. This can be done by applying thermometers or measuring the increase in resistance, but neither of these methods gives the maximum temperature, which is the important value as regards the safety of the machine, and which under certain circumstances can differ considerably from the values obtained by thermometer or resistance measurement. This fact is allowed for in the various rules by

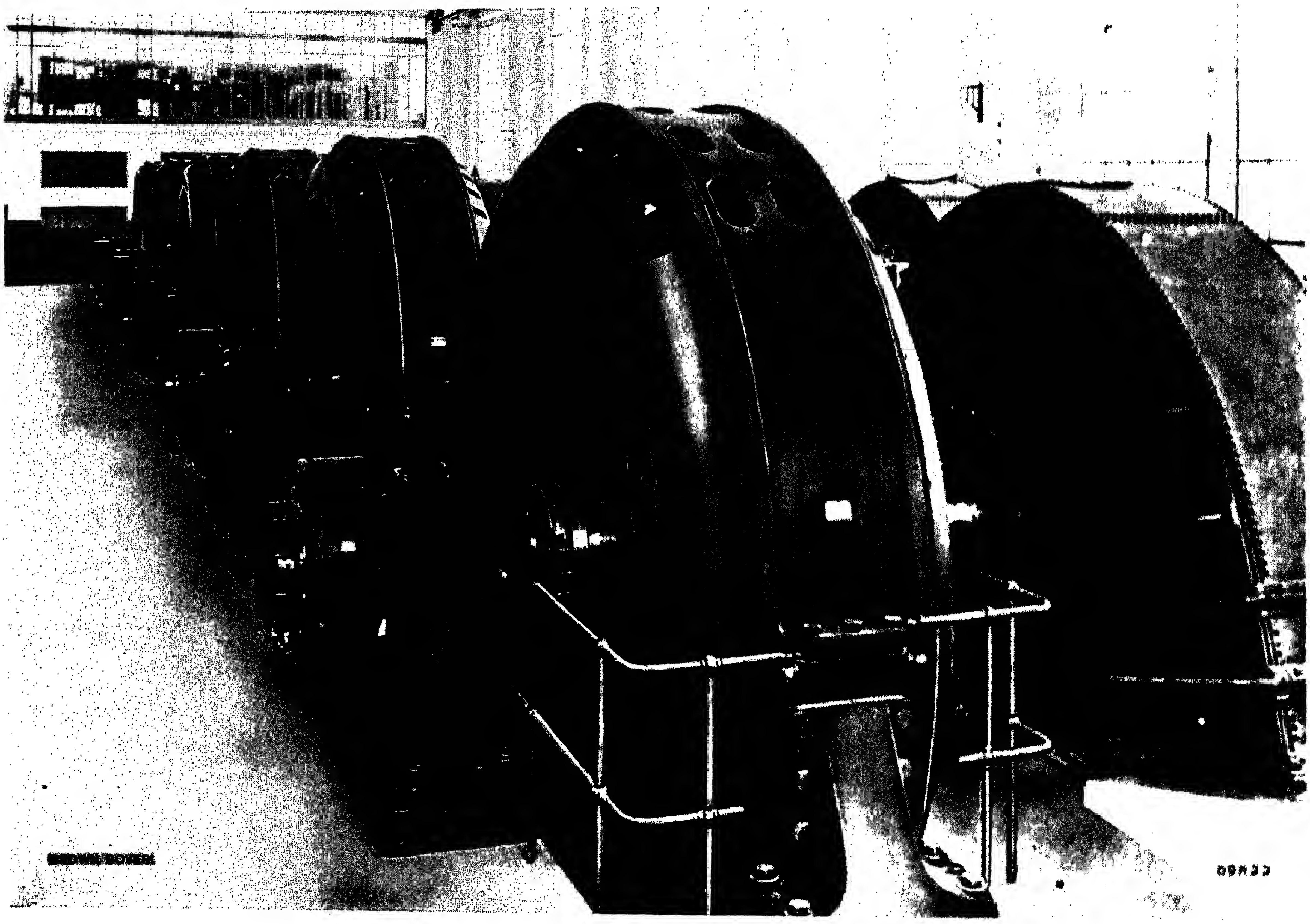


Fig. 32. Six three-phase alternators each 2640 kVA, 17,600 V, 40 cycles, 300 r. p. m., in the Kallnach Central Station of the Bernese Power Supply Co.

providing a certain factor of safety in the maximum temperatures permitted; a measure which is quite satisfactory when the dimensions of the machines are not too great, but not for large and powerful machines, particularly when the length of the iron core is considerable.

For this reason it has recently become customary to use thermo-couples or resistance elements, which are built into the machine at various points during the construction, and thus enable the actual temperatures to be measured when the machine is in operation. It is consquently possible to tell accurately at any time whether the machine is capable of taking a greater load, or whether the load should be reduced.

The instruments indicating the temperature can be installed either near the machine or on the switchboard. Elements situated within the high-tension windings are connected to the instruments by means of protection transformers in order to prevent the measuring instruments being connected directly to the high-tension windings.

Brown, Boveri & Co. have fitted these devices on a number of generators although they are only applicable to large units on account of the relatively high cost. Further, it should be mentioned that, if agreed upon when the order is placed, these elements built into the machine may be employed to determine if the temperature rises of the machine in question, are in accordance with those specified in the standard rules or special guarantees.

THE STATOR TERMINALS

The ends of the stator winding are brought out to terminals, the number of which depends upon the current system and method of connections employed. These terminals are usually mounted upon either porcelain insulators, or bushings of porcelain or bituba, and are arranged for connection to busbars or cables according to the current or other conditions relating to the installation. The terminals are always fitted so that they are protected against accidental contact, but are easily accessible in case of necessity.

THE END SHIELDS

For protecting the windings and the rotating parts, the stator is provided with end shields made of cast iron or sheet iron and consisting of a number of parts; they are easily removable. The end shields of open machines are provided with apertures round the whole circumference (Fig. 1), but those of the protected and enclosed machines are completely closed and are provided with easily removable inspection covers.

THE ROTOR

The type of the rotor or pole wheel depends upon the manner in which the poles are attached, which again depends upon the diameter of the rotor and the speed. Apart from special designs which only come into question in particular cases, the following methods of pole fixing are generally adopted in Brown Boveri alternators: —

1. **Poles bolted in position** (Fig. 33 and 34). Each pole is attached to the rim of the wheel by means of one or more bolts. This method can be employed for any number of poles and wheel diameter as long as the peripheral speed does not exceed 30—40 m/sec. The poles are castings of dynamo steel, the pole shoes forming one piece with the core and at the same time serving to hold the magnet coils in position (see Fig. 34). The wheel itself is also a steel casting; when the diameter is small it is of the one-piece disc type, and when large, of the spoked type either in one or more parts. Division into a number of parts is not only due to considerations of weight and space for transport, but is necessary with heavy wheels owing to the difficulties otherwise encountered in casting. The wheel sections are joined together according to circumstances by bolts, connecting lugs, or shrink rings. Rotors of small diameter particularly those of small machines with four to eight poles, are pressed directly on to the shaft, the two being dispatched together. With larger diameters, fixing is as a rule effected by means of shrink rings and a key on the shaft, the wheel and shaft being dispatched separately.

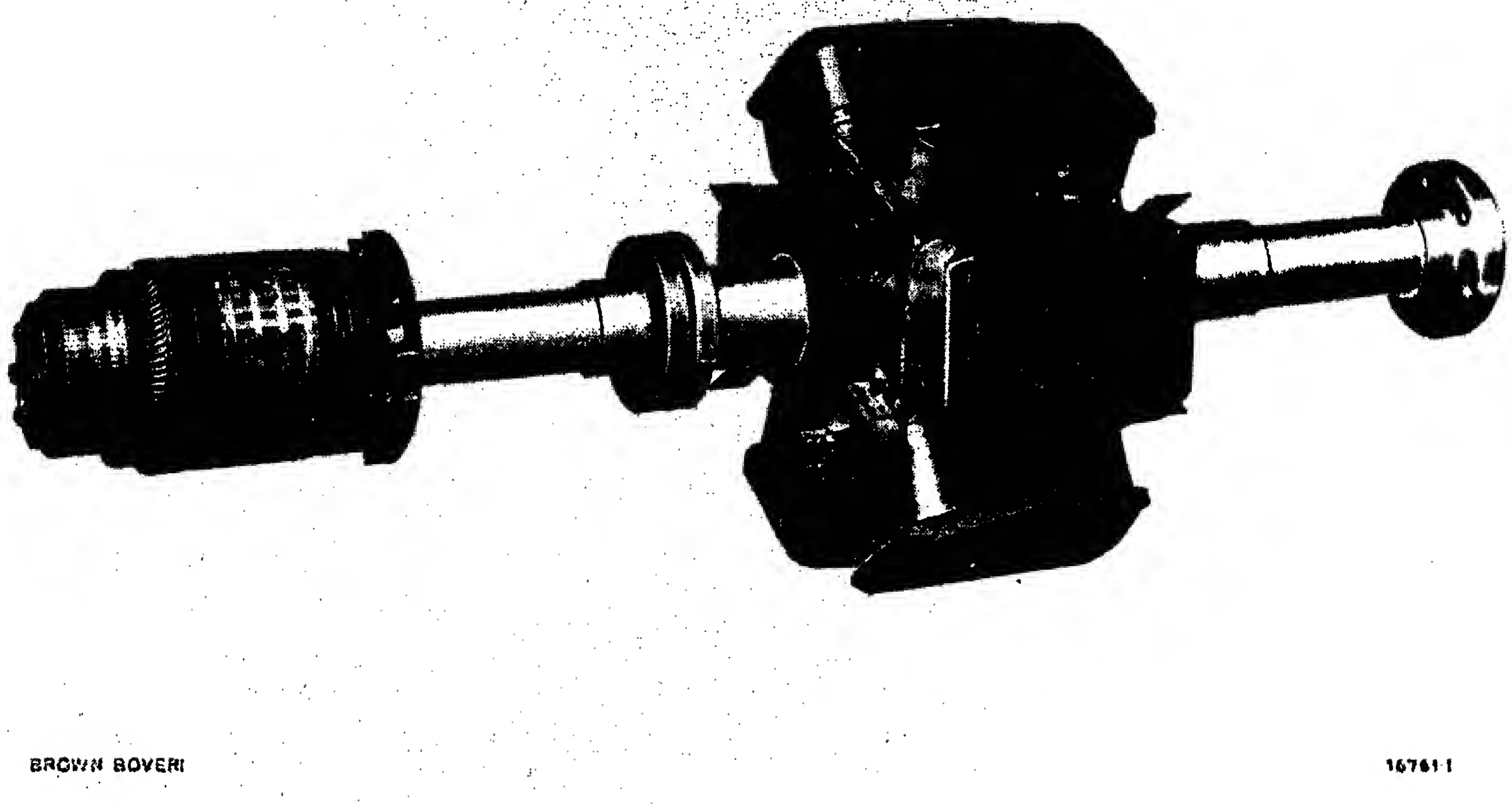


Fig. 33. Rotor of a three-phase alternator, 700 kVA, 1000 r. p. m.

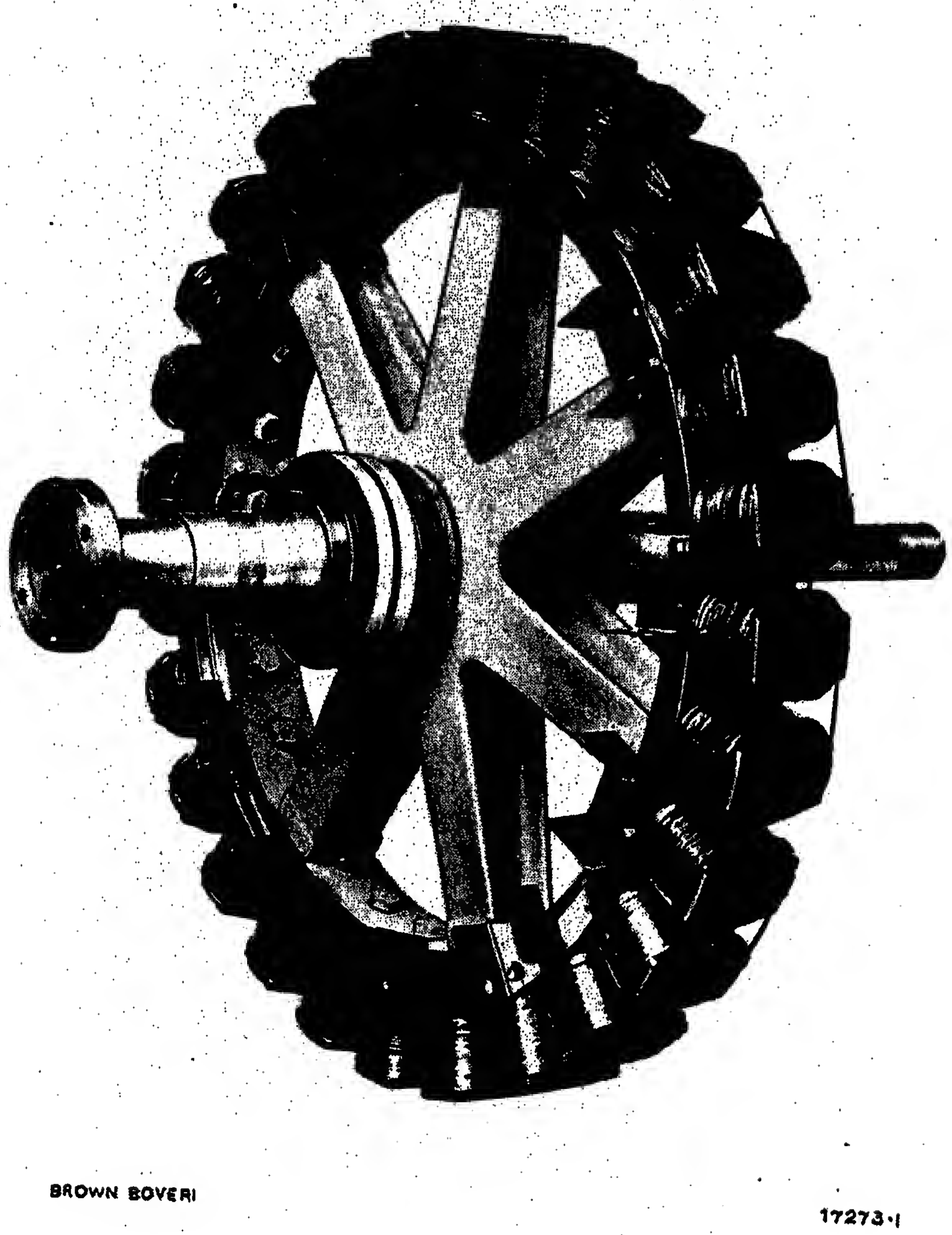


Fig. 34. Pole wheel of a vertical-shaft, three-phase alternator, 290 kVA, 215 r. p. m.

2. **Pole shoes bolted on.** Rotors constructed on this principle have the pole cores in one piece with the cast-steel wheel rim (Figs. 38 and 39), the pole shoes, which are also of cast steel, being attached by means of bolts. This type is employed for machines having four to sixteen poles and peripheral speeds of 40—50 m/sec. In order to enable the material to be adequately tested, when the axial length of the rotor is great, the rim is built up of a number of discs.

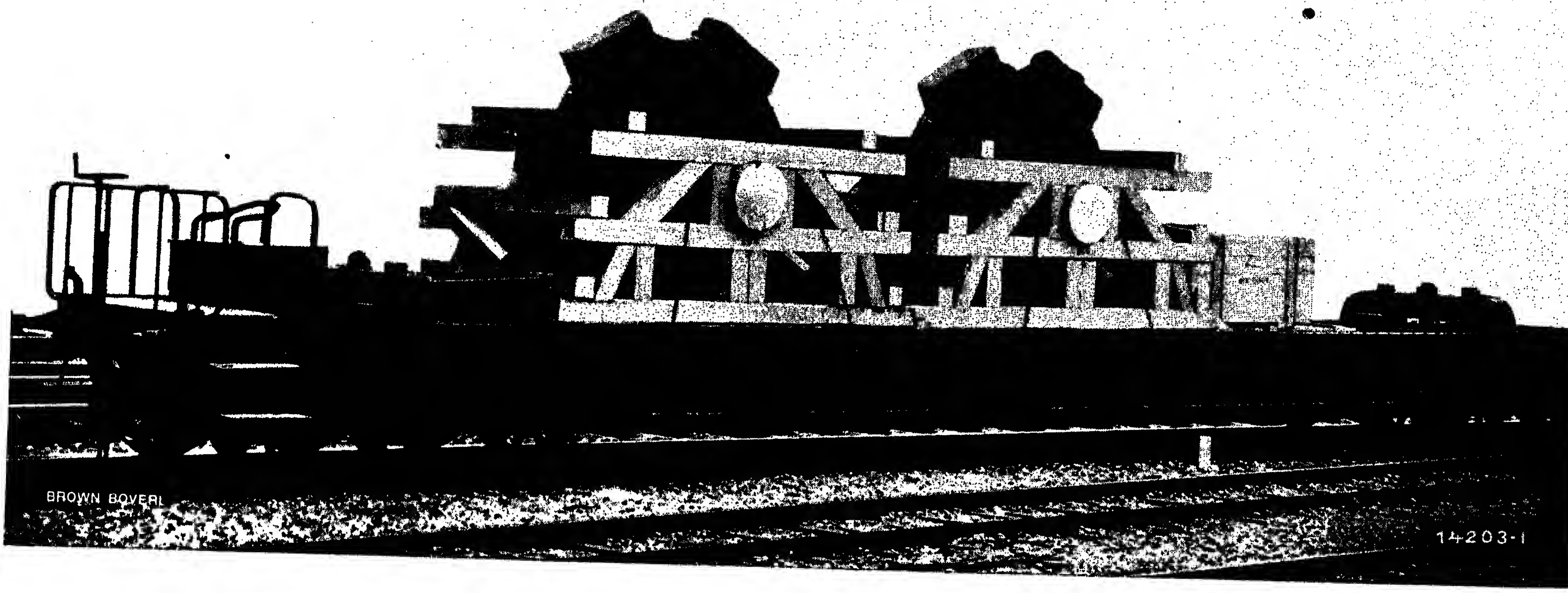


Fig. 35. Transport of two parts of a rotor spider on a special truck.

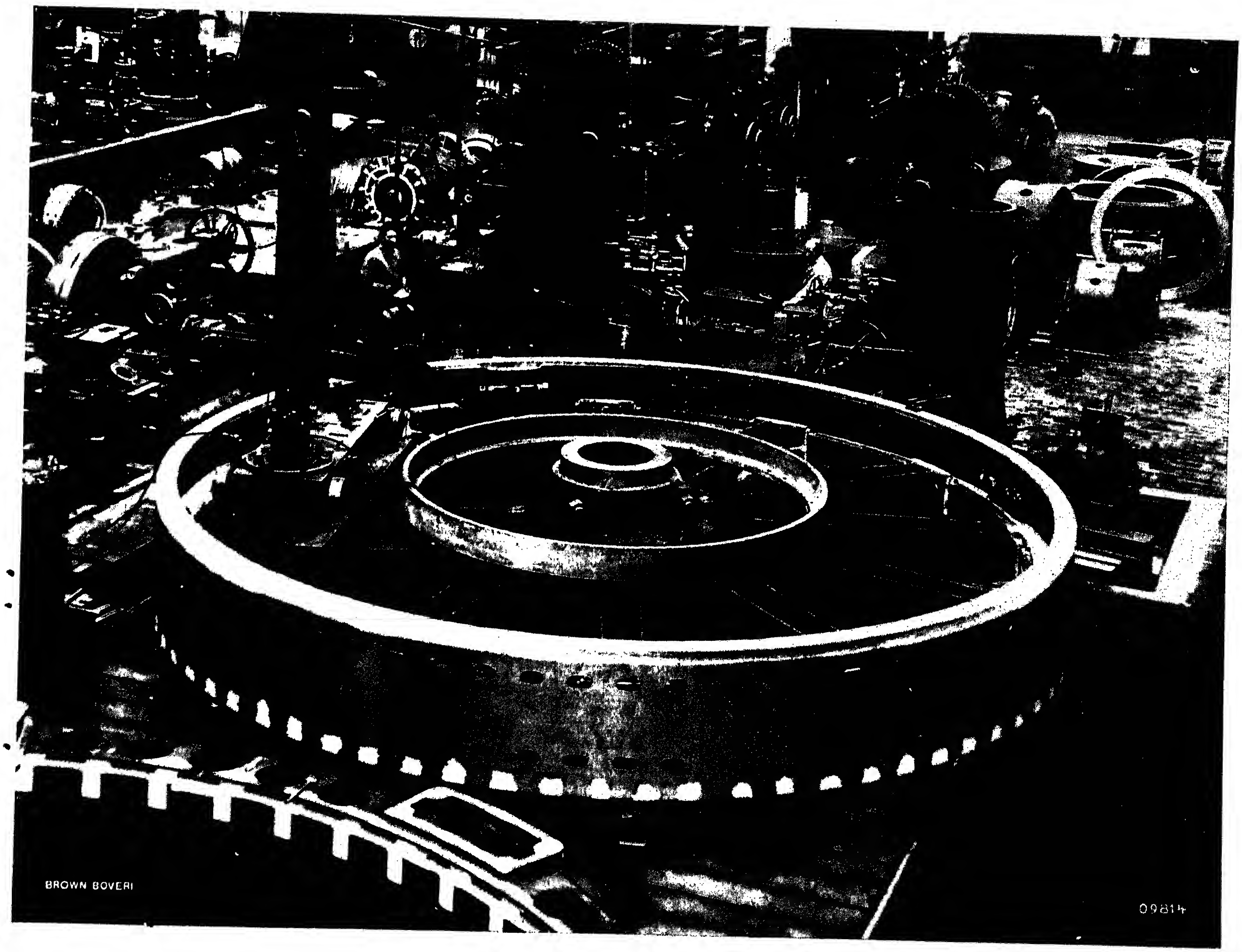


Fig. 36. Machining the pole wheel of a three-phase alternator, 7050 kVA, 83·3 r. p. m.

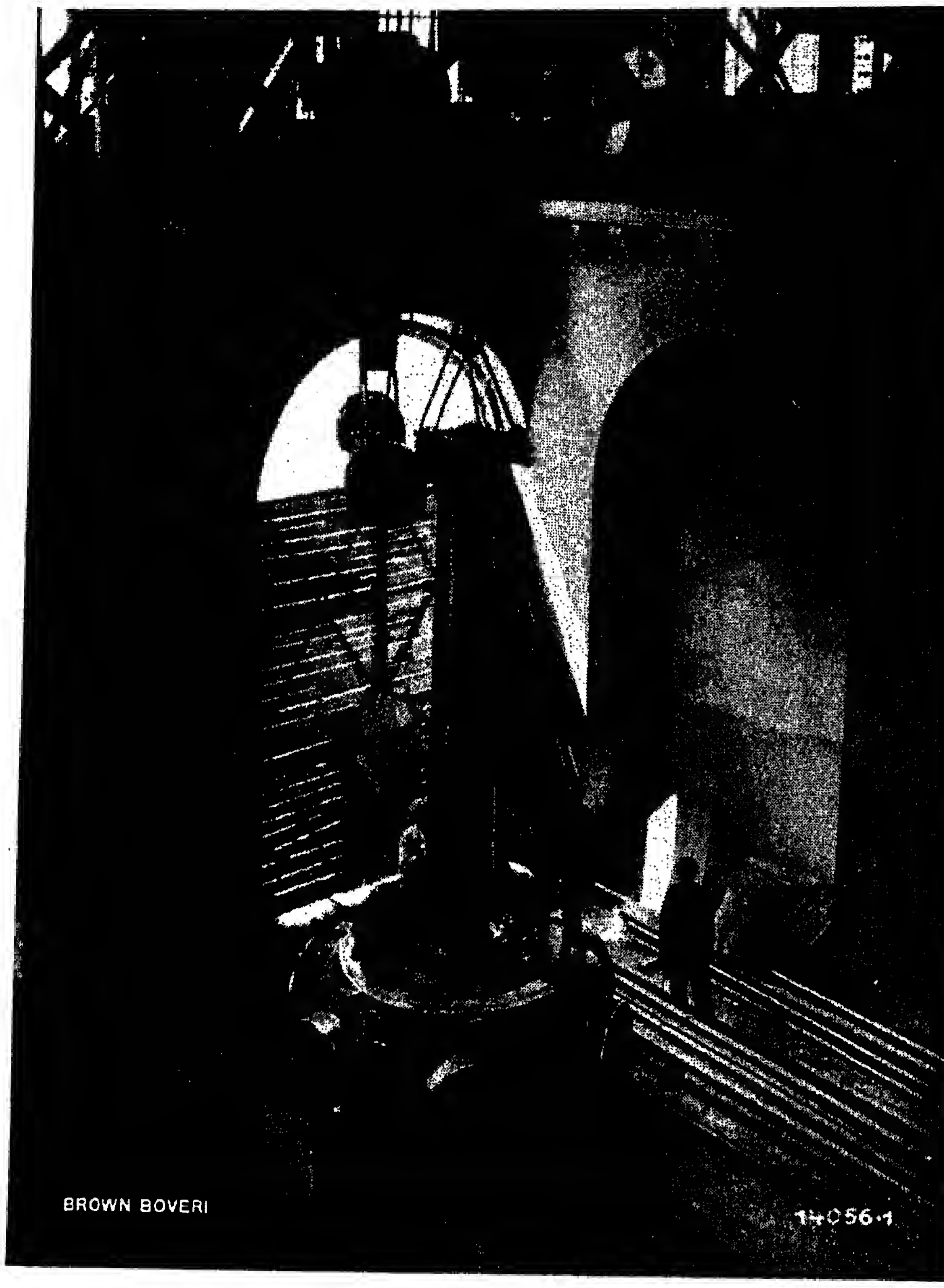


Fig. 37. Assembling the rotor spider and shaft of an alternator
at the Ritom Power Station of the Swiss Federal Railways.

Wheel rims of small diameter are either pressed or shrunk directly on to the shaft, and must therefore be designed with the idea of delivery with the shaft fixed in position. For larger rotor diameters, the wheel rim is mounted on a boss or a spider of cast iron or cast steel, which is fixed to the shaft by means of keys and shrink rings. In this case the shaft can be dispatched separately if necessary.

3. **Dovetailed poles** (Figs. 40—42). The poles with cast-on pole shoes are provided with massive dovetails which fit into corresponding grooves in the rim of the wheel. This method is employed for rotors with eight poles and more and for peripheral speeds up to about 70 m/sec, and consequently when the output is great.

The wheel rim consists of discs of either cast steel or wrought Siemens-Martin steel according to the stresses. As the thickness of these discs is relatively small and they are machined on all surfaces, there is every opportunity of testing for faulty material. In large rotors, spaces are left between the discs to allow

Fig. 38. Dressing a rotor spider.

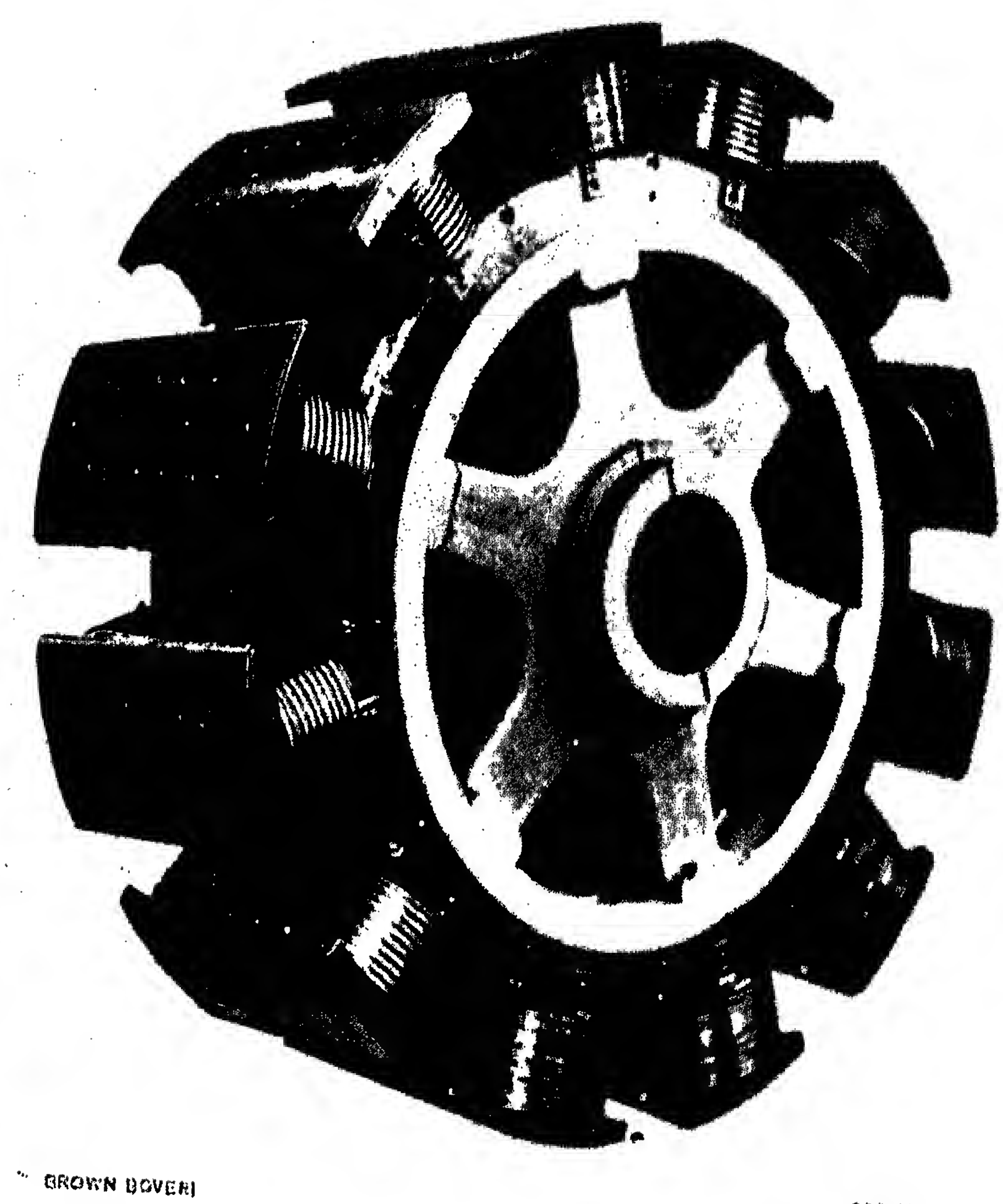


Fig. 39. Pole wheel of a three-phase alternator, 7000 kVA, 500 r. p. m.

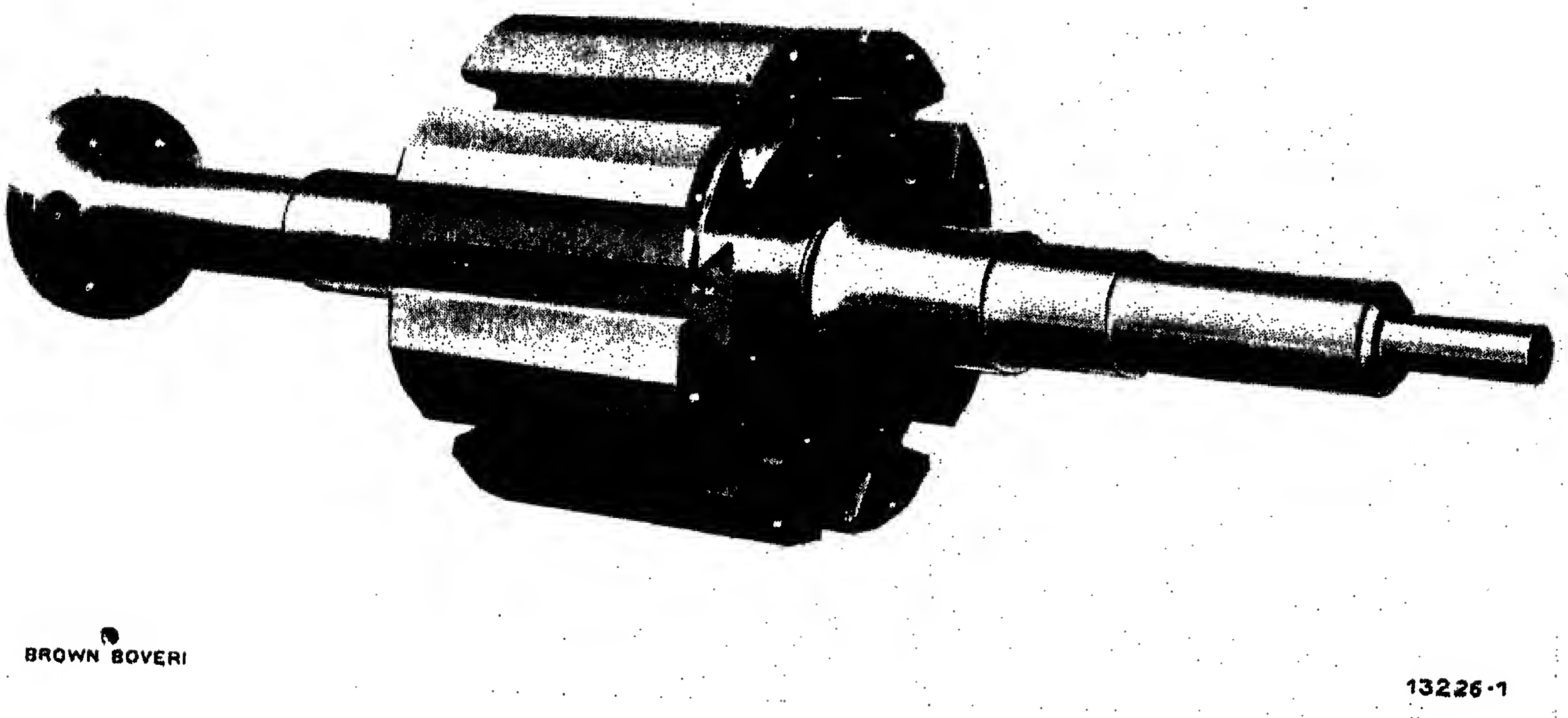


Fig. 40. Rotor for a three-phase alternator, 4000 kVA, 750 r. p. m.; showing dove-tail slots.

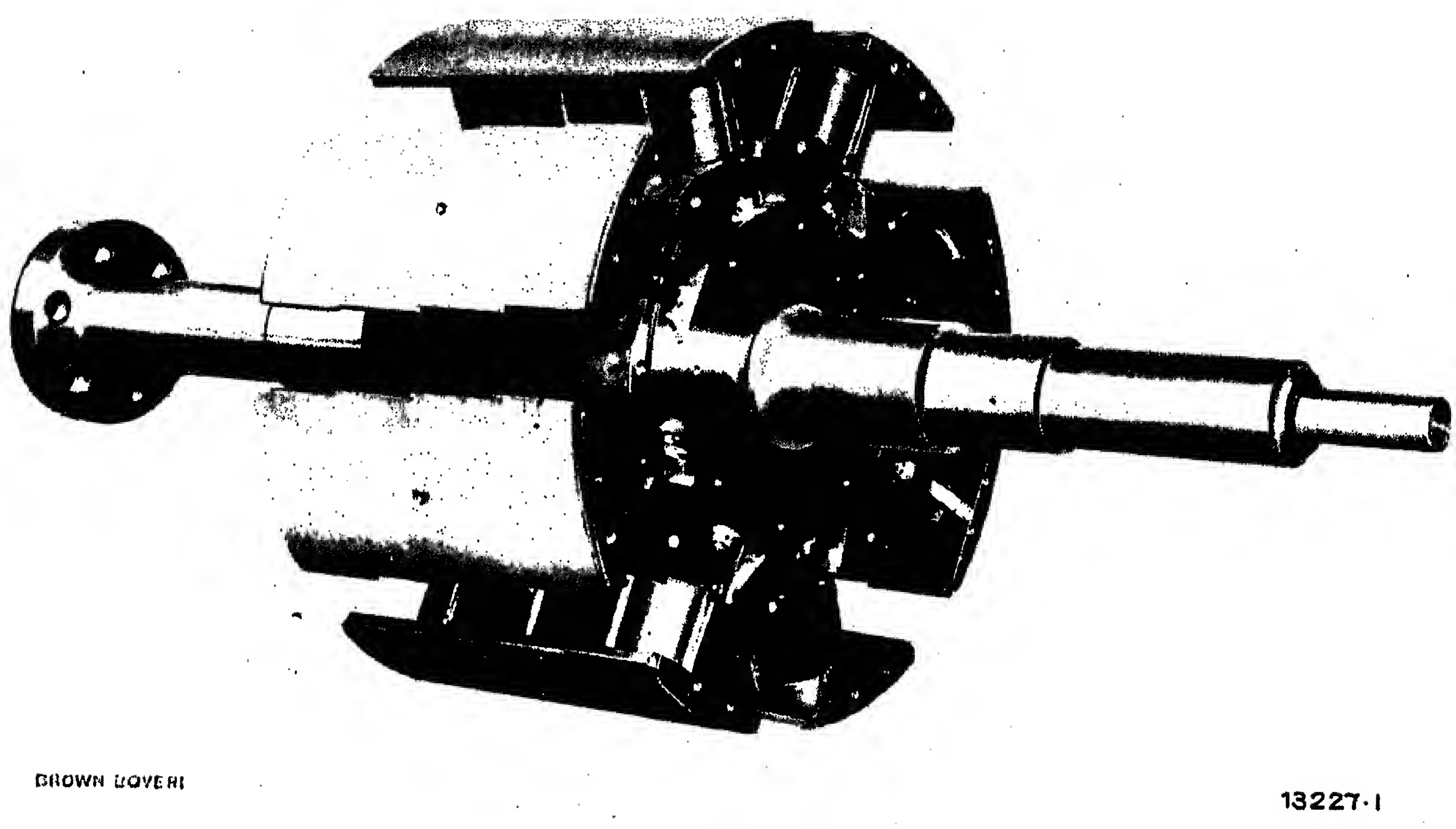


Fig. 41. Rotor after the poles have been fitted.

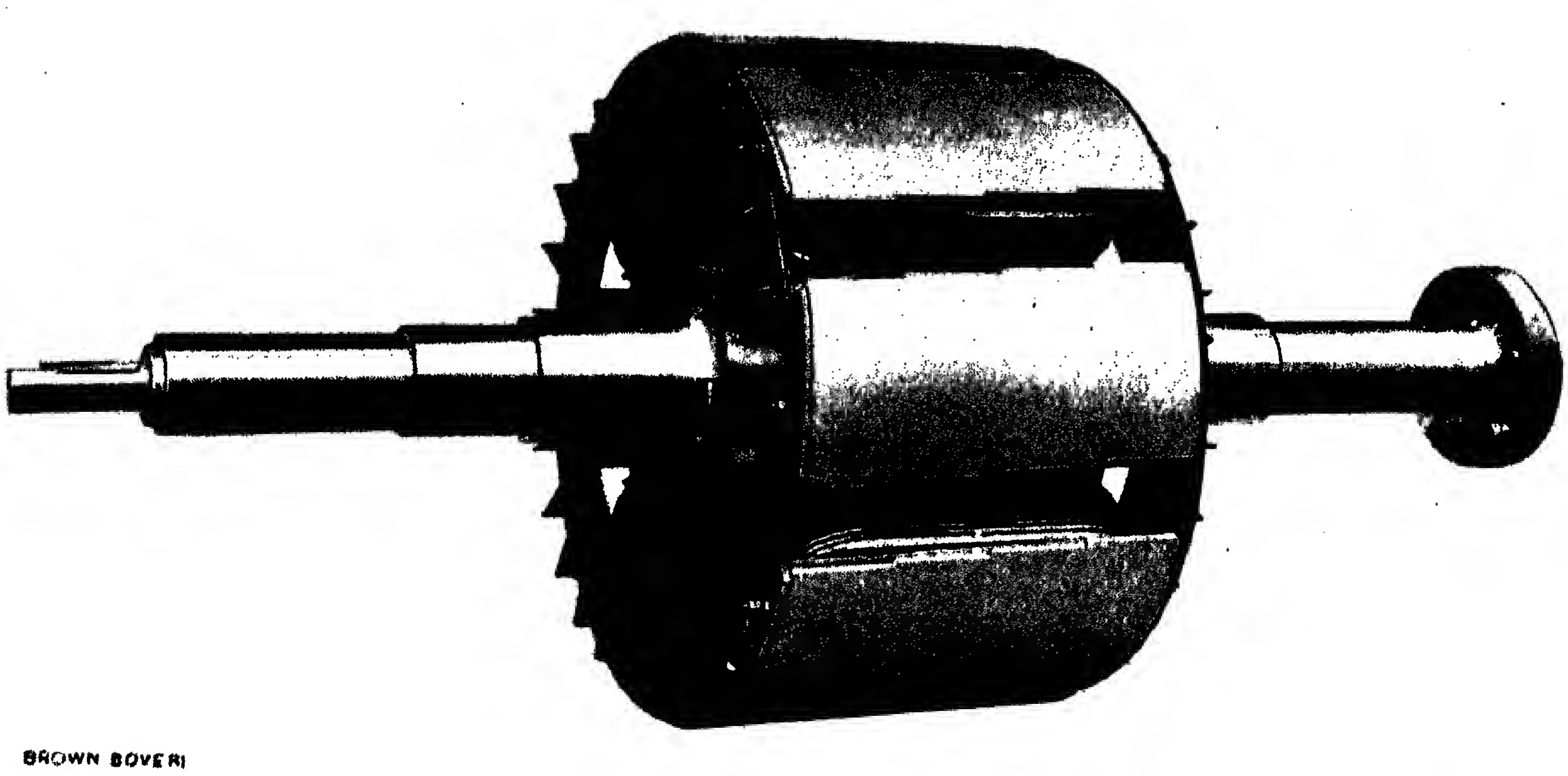


Fig. 42. Above rotor completed.

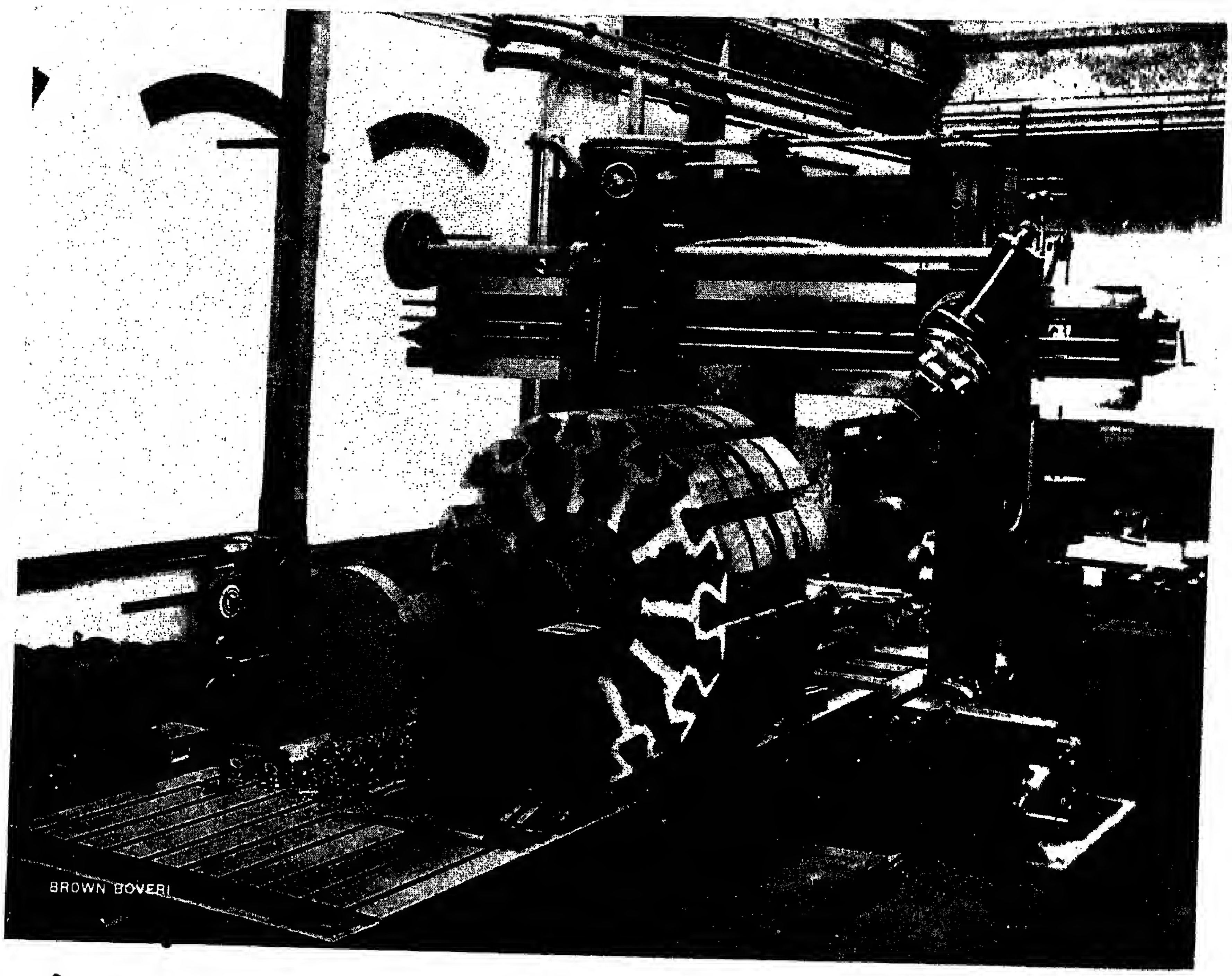


Fig. 43. Rotor of a three-phase alternator 16,500 kVA, 500 r. p. m. on a planing machine for the finishing operations on the dovetail grooves.

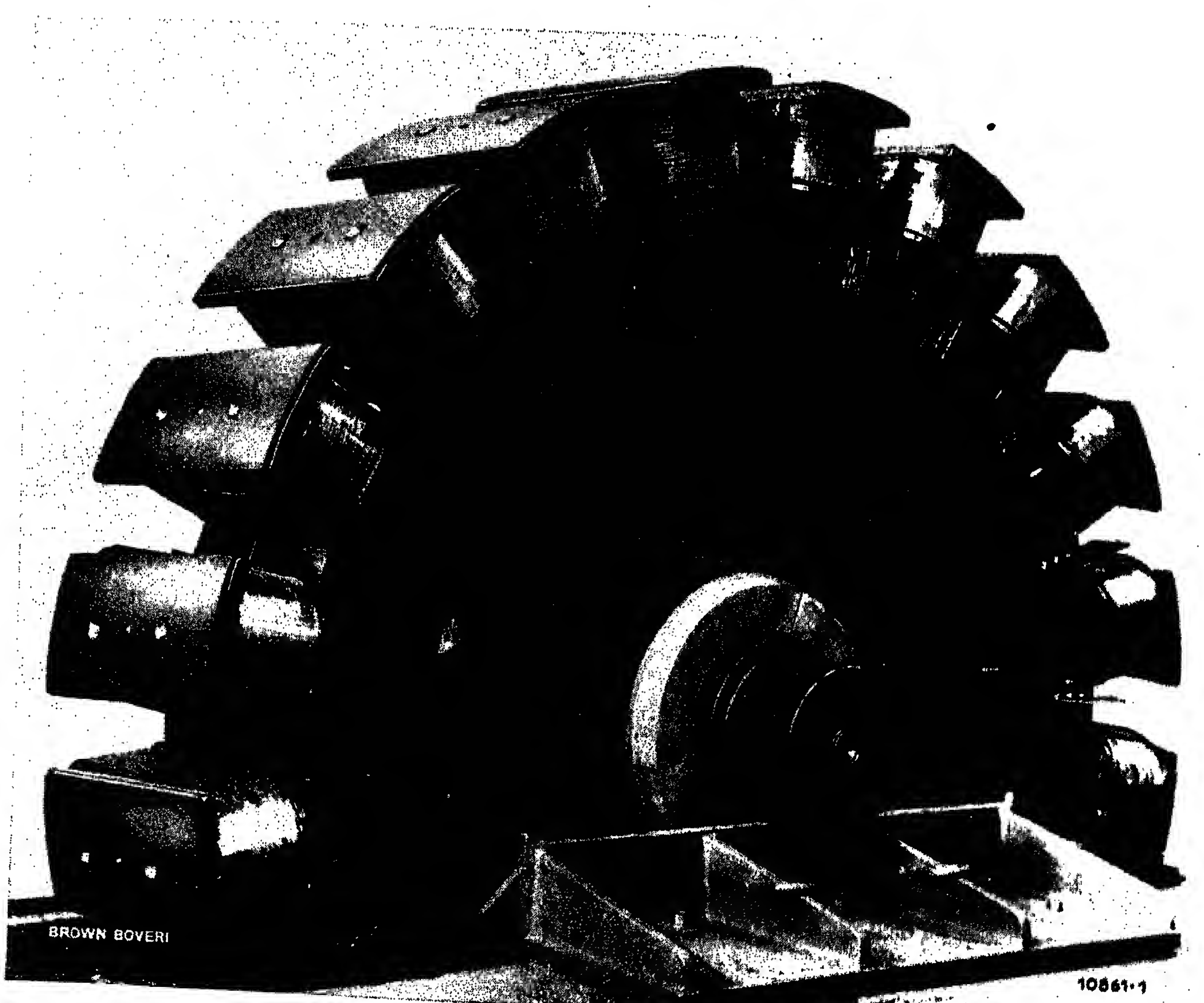


Fig. 44. Statically balancing a finished rotor for a 12,000 kVA, three-phase alternator to run at 300 r. p. m.

the passage of cooling air (Fig. 43). The dovetails on the poles and recesses on the wheel are accurately machined so as to ensure perfect fitting. The slight play necessary for sliding the pole into position is taken up by bolts or keys so that each pole is fixed absolutely firmly in position. When the rotor diameter is small, the rim is shrunk directly on to the shaft, the two being then considered as one piece; wheels of greater diameter are shrunk onto a cast-iron or cast-steel spider which is fixed to the shaft by means of keys and shrink rings (Fig. 44).

The **pole shoes** are independent of the rotor design, and are, as a rule, solid (always when the stator slots are of the half-open type). Only when the stator has open slots, or when the generator is either a single-phase machine or a three-phase machine, likely to be subjected to heavy unbalanced loading are laminations placed on to the solid pole shoes. The pole shoes are stepped (Fig. 42) or set slanting (Fig. 33, 34, and 39)

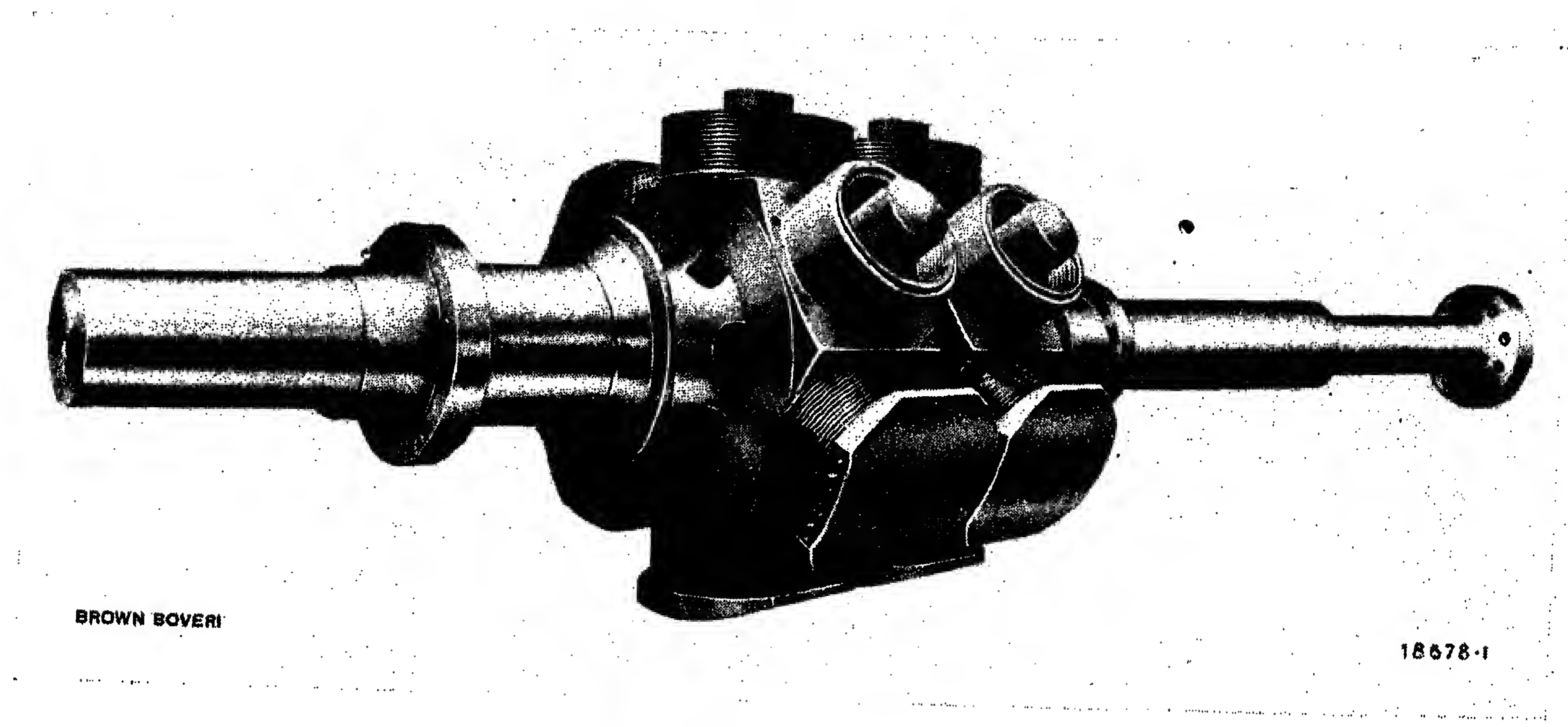


Fig. 45. Rotor with screwed pole shoes for a three-phase alternator, 7300 kVA, 1000 r. p. m. for the Stà. Forze Idrauliche della Maira.

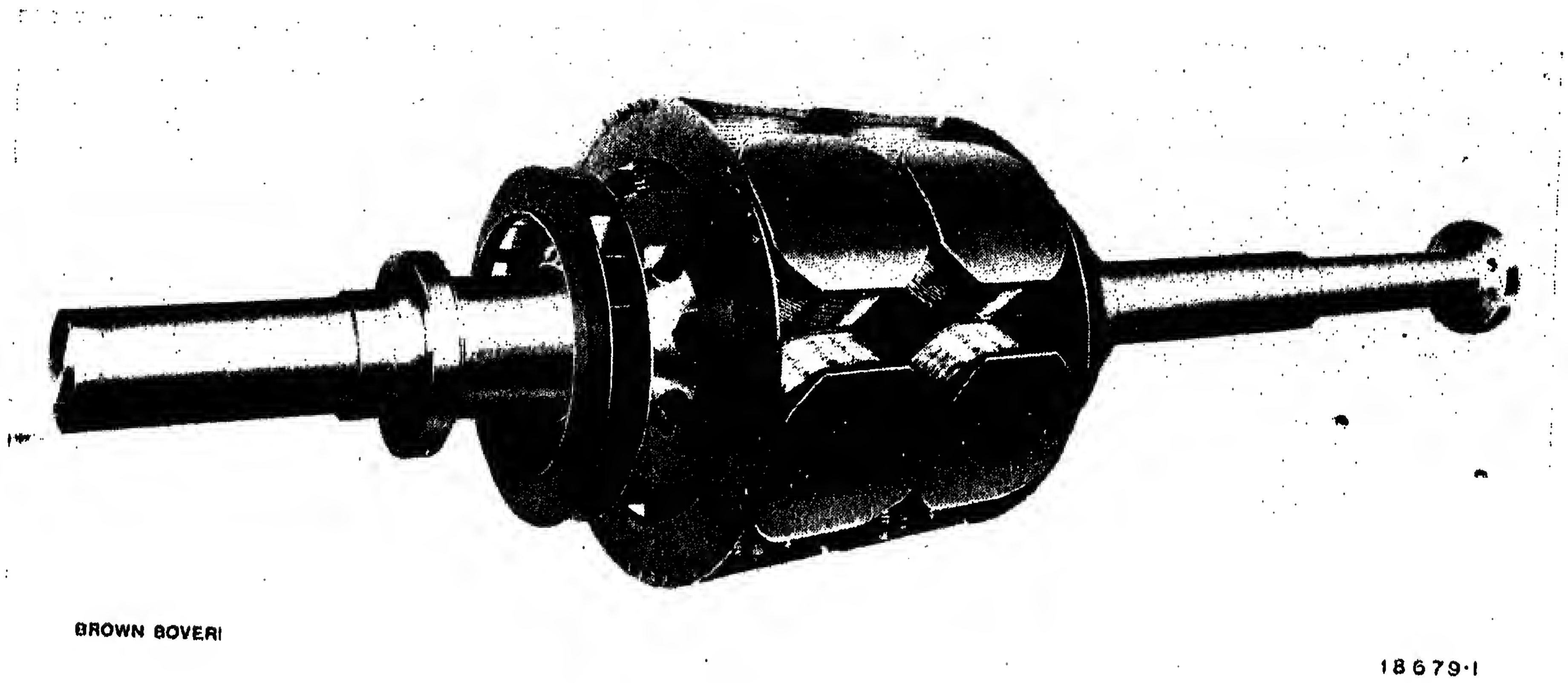


Fig. 46. Completed rotor, with screwed pole shoes, for the three-phase alternator mentioned above.

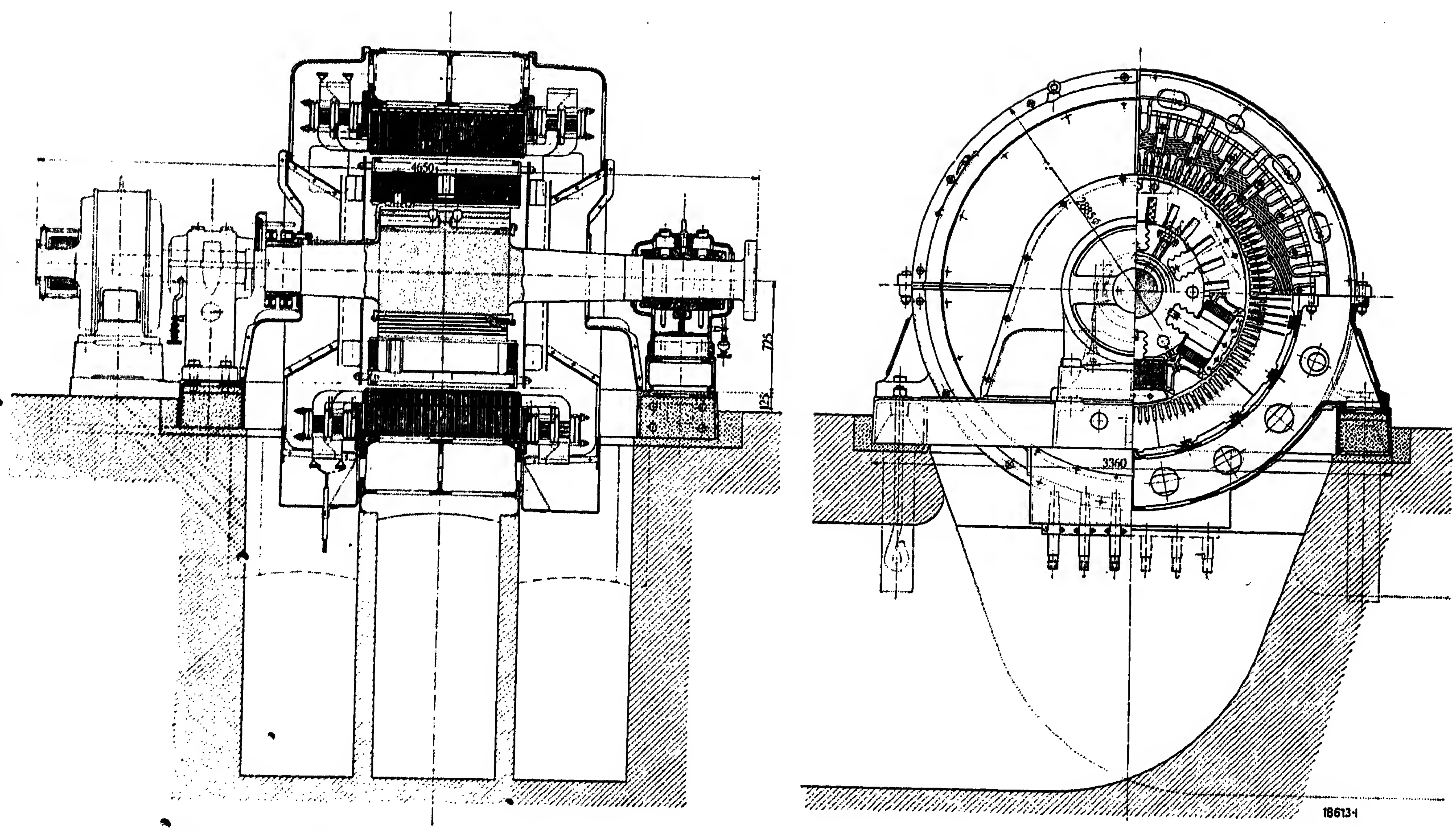


Fig. 47. Section through a three-phase alternator, 5000 kVA, 5300 V, 42 cycles, 840 r. p. m. for the Brasimone Central Station of the Stà. Bolognese di Elettricità, Bologna.

with regard to the axis, in order to obviate harmonics being set up in the voltage wave by the slots. By suitably designing the pole shoes, a practically sinusoidal wave form can be obtained.

For the sake of completeness, some further examples of special rotor designs may be given, such as are occasionally necessary to satisfy special conditions. Figs. 45 and 46 show a pole wheel as employed for 4 and 6-pole rotors. The pole wheel consists of one or more cast-steel spiders upon which the pole shoes are screwed by means of strong buttress threads. It is an advantage if circular pole coils can be used, as they are the easiest to wind and require no special strengthening against the action of centrifugal force.

The poles of the rotor shown in Fig. 47 are attached by a special dovetail fixing, the wheel rim forming one part with the shaft.

Fig. 48 shows a multi-pole rotor, the poles of which are attached by bolts; the rim consists of two cast-steel rings of L section machined on all faces, enabling the material to be easily examined for flaws.

The rotor in Fig. 49 is for a slow-speed alternator, the wheel of which is built up out of a two-part spider and a four-part rim. The various parts are connected by means of suitable flanges, plates, and bolts. The wheel is made entirely of cast steel and by dividing it into a number of sections it is possible to minimise the thickness and consequently the weight of the whole wheel, with a maximum of safety; the separate parts being so simple that they present no difficulty in casting.

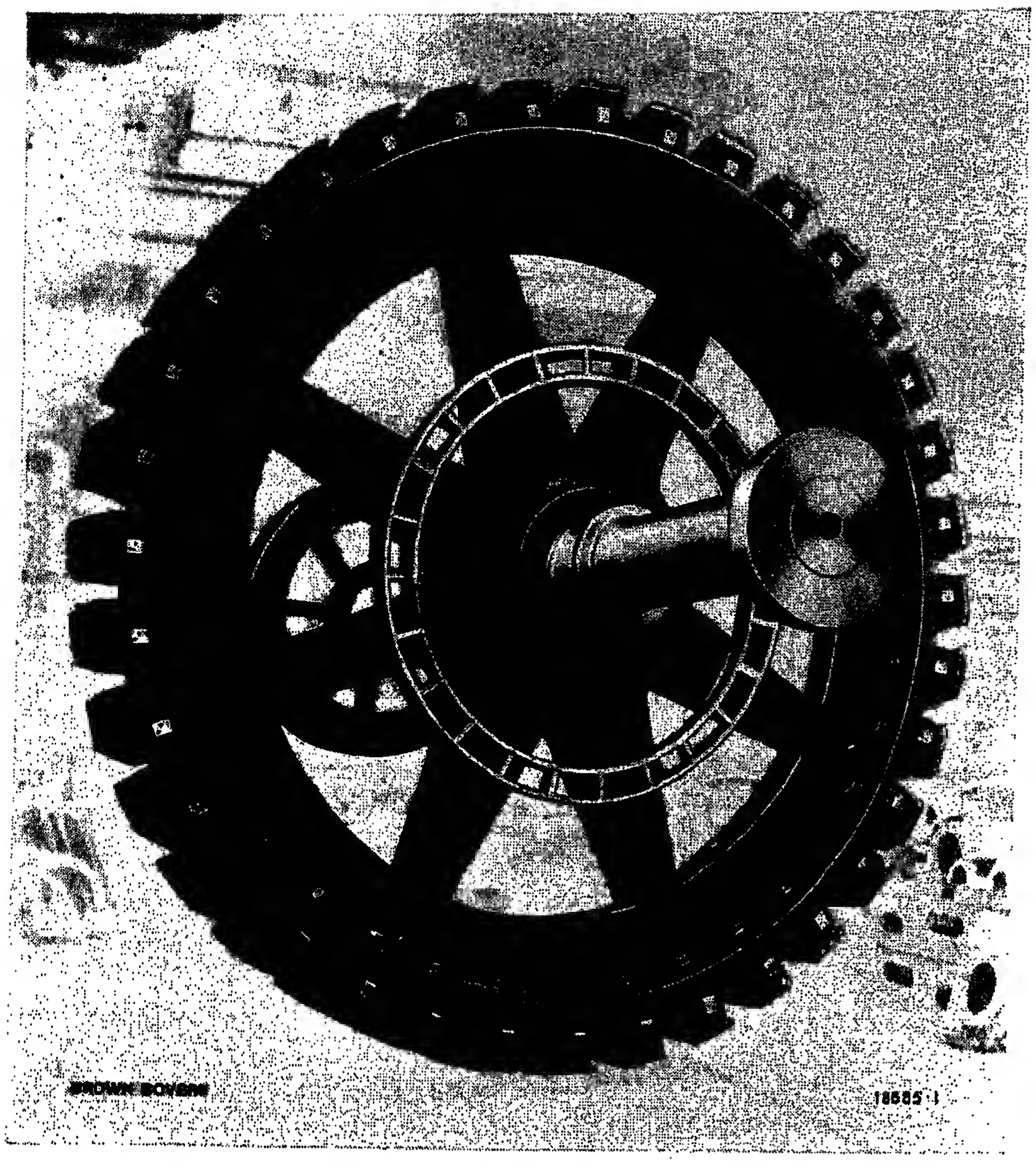


Fig. 48. Complete pole wheel of one of the three, vertical-shaft, three-phase alternators, 6000 kVA, 5400 V, 50 cycles, 167 r. p. m., for the Mühltal Central Station of the Isar Power Supply Co.

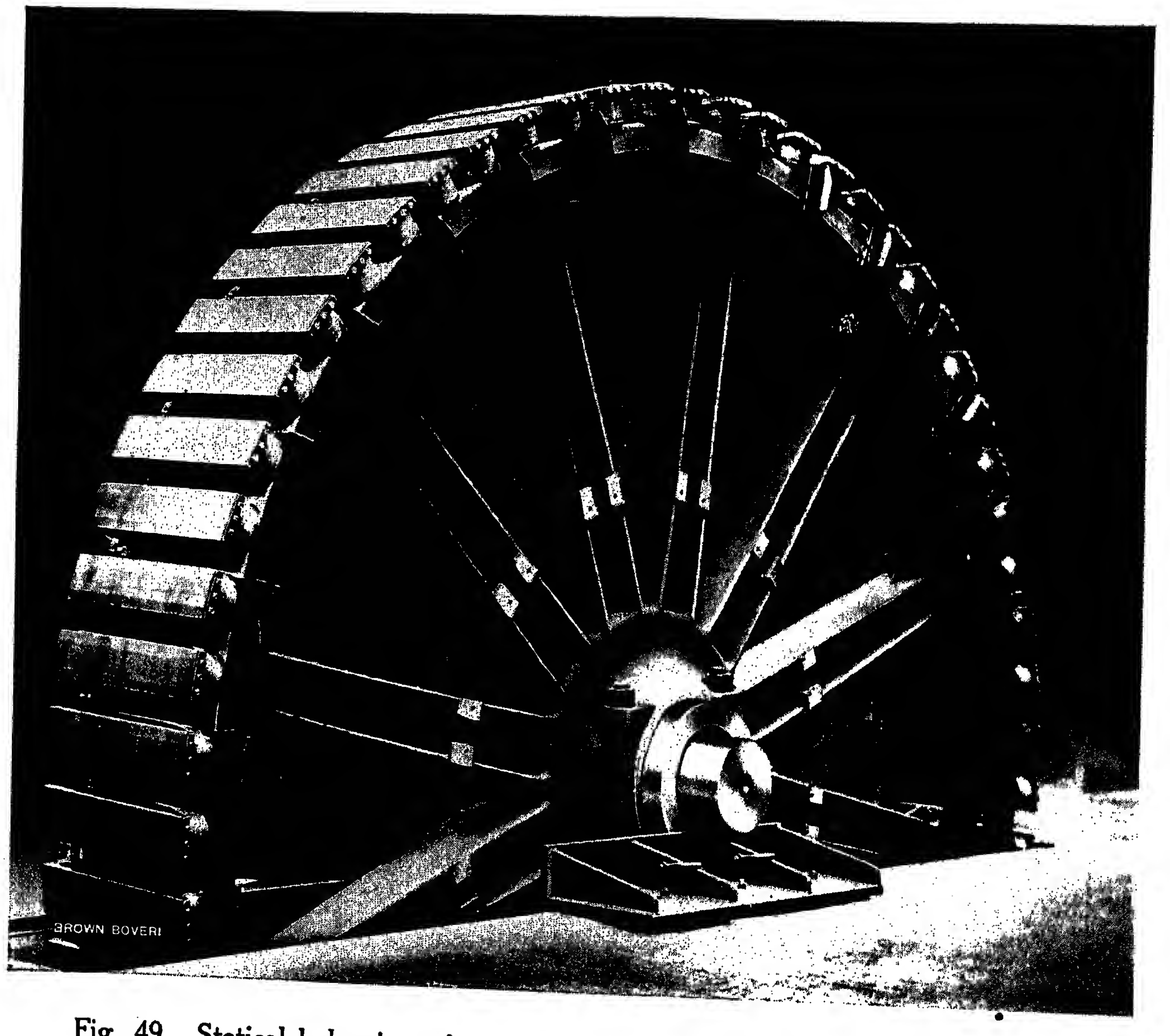


Fig. 49. Statical balancing of a completed rotor for a vertical shaft alternator, 7050 kVA, 83·3 r. p. m.

Fig. 50 shows the pole wheels for the single-phase alternators installed in the Ritom power station of the Swiss Federal Railways. The pole shoes are screwed on to the threaded cores in a similar manner to cap nuts.

These few examples should be sufficient to show that, although limited by considerations of economical manufacture to certain well defined types of construction, the designer is nevertheless fully able to satisfy unusual conditions if necessary.

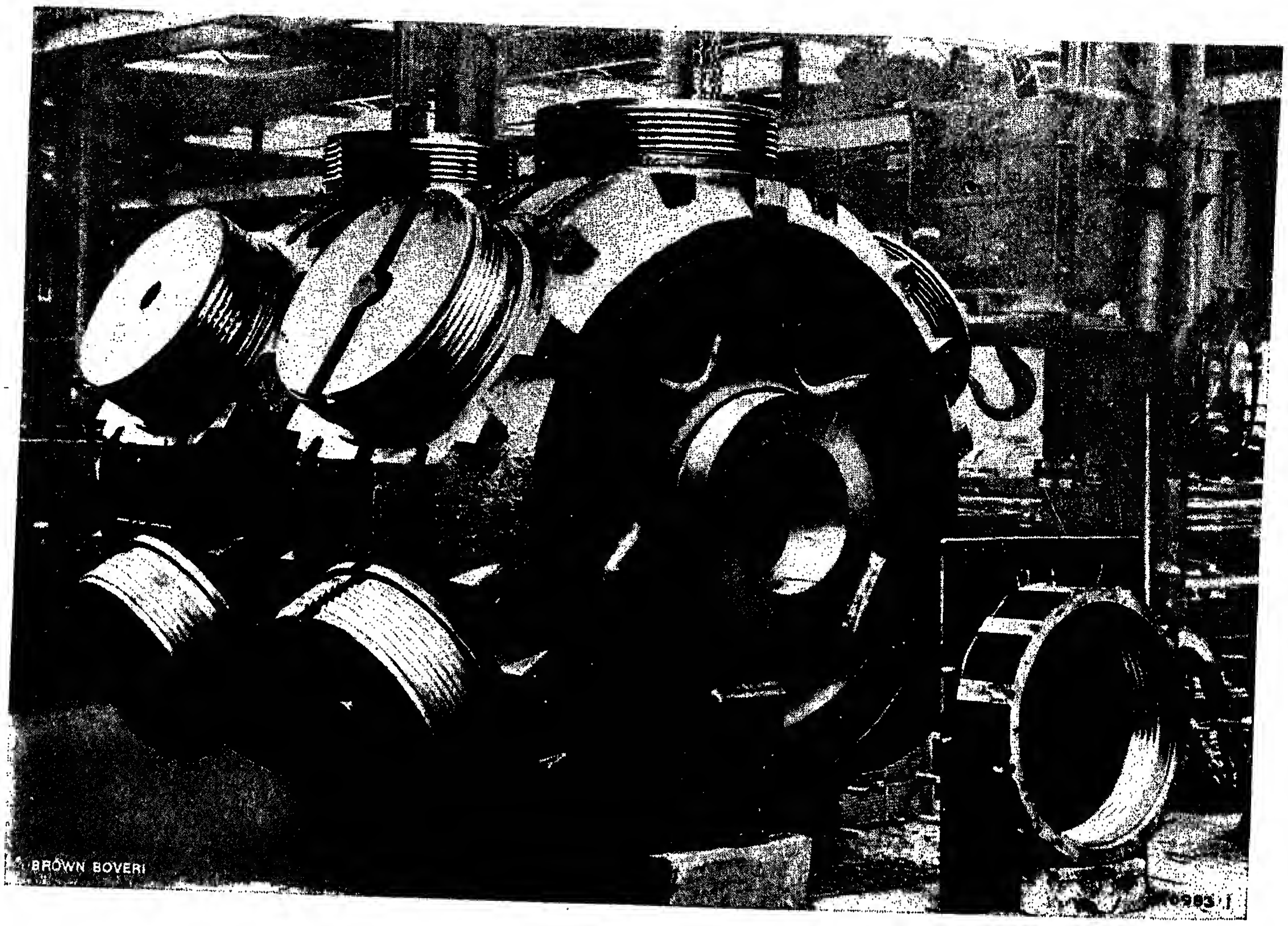


Fig. 50. Pole wheels for the single-phase alternators, 9000 kVA, 333 r. p. m., for the Ritom Power Station of the Swiss Federal Railways.

THE DAMPING WINDINGS

As a rule, damping windings in the pole face are only employed for large single-phase alternators, as the solid pole shoes of three-phase alternators provide a considerable damping effect and it is only necessary to employ special windings in particular cases. The purpose of these windings is to damp out, as far as possible, the harmonics occurring in single-phase current and so to minimise the losses which they occasion. When fitted to three-phase machines, they are intended mainly to reduce the harmonics which occur when one phase is short-circuited, and which under

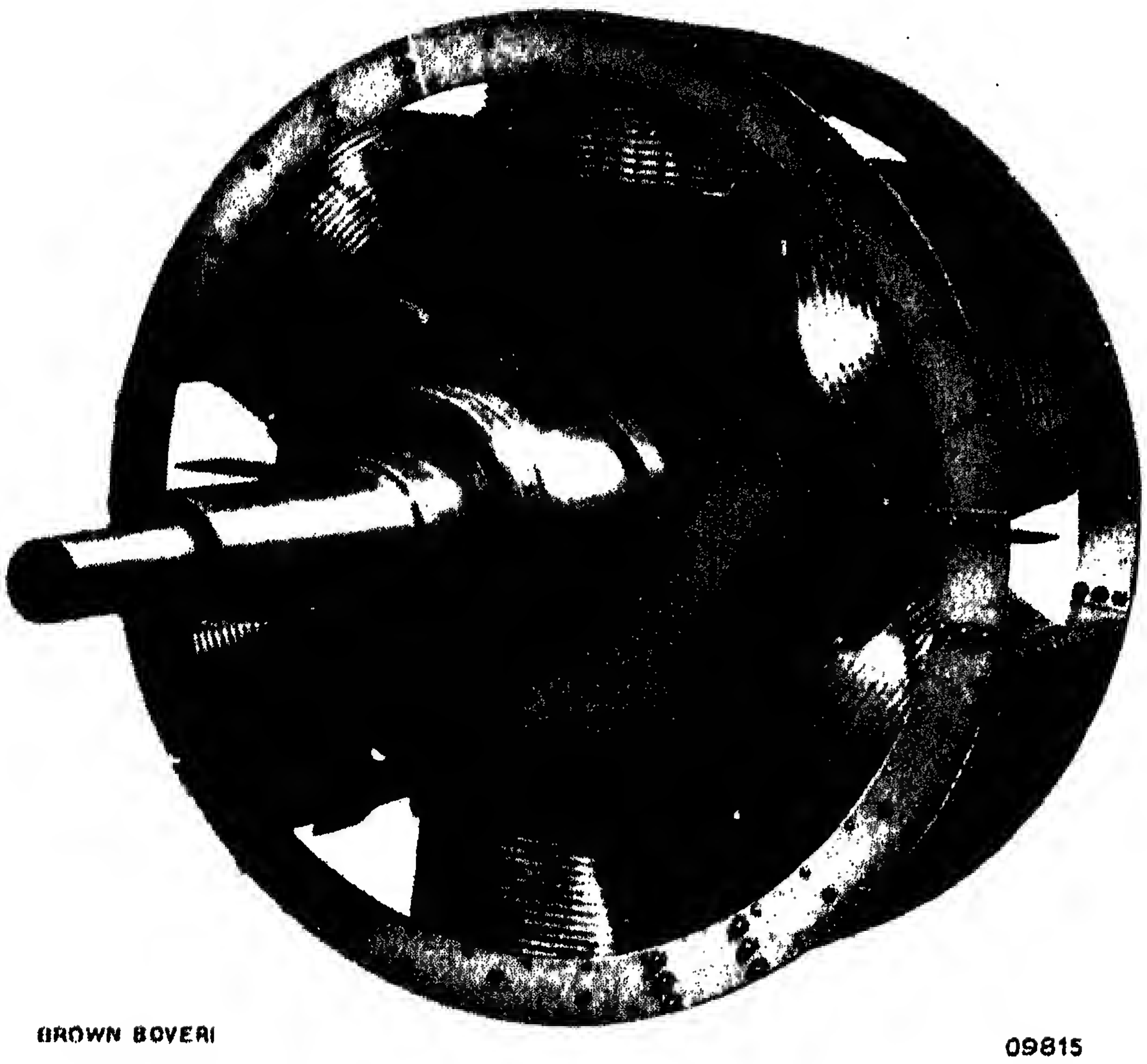


Fig. 51. Finished rotor with damping winding for a single-phase alternator, 2500 kVA, 500 r. p. m.

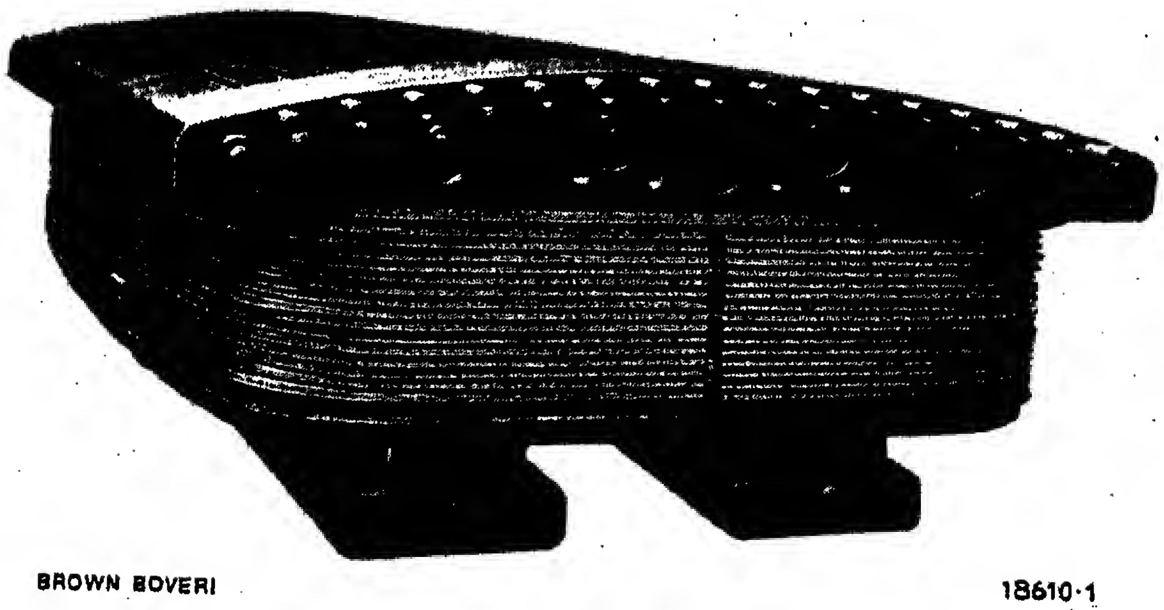


Fig. 52. Pole with laminated pole shoes and damping winding for a single-phase alternator 10,650 kVA, 250 r. p. m.

certain circumstances can give rise to excessive voltages as a result of resonance with the transmission line.

The damping windings consist of massive bars of circular section placed in corresponding holes in the pole shoes and connected to copper rings at both ends (Fig. 51). This connection is made either by brazing or, under certain circumstances, by autogenous welding. When the pole shoes are very large, as in the case of single-phase alternators for railway use, for example, a flexible connection is placed between the damping bars and the rings, which allows for the unequal expansion of the bars. Wherever the design of the poles or pole shoes makes it necessary, the rings are divided into sections and fastened together with bolts and clips.

THE ROTOR WINDING

The rotor winding consists of separate, specially wound coils which are slid onto the pole cores and held in a radial direction between the pole shoe and wheel rim. For small excitation currents, the coils are of rectangular-sectioned copper wire insulated with several layers of cotton or paper treated with a special insulating substance so that each forms a solid body capable of withstanding without deformation the centrifugal forces occurring.

With higher excitation currents, i. e., for larger alternators, the coils consist of bare copper strip wound on edge, the turns being insulated from each other by layers of varnished presspahn or asbestos. The coils wound in this manner are baked under pressure, the final product being a solid body of great mechanical strength. The cooling surface of large coils is considerably increased by including, at intervals, single turns of broader strip than that used for the greater part of the coil; these turns project beyond the remainder and constitute cooling vanes (Figs. 39, 42, and 52). In other cases, when the copper strip is of any considerable thickness, the cooling surface is increased by employing copper having a cross-section as shown in Fig. 53, so that the resulting coil has a corrugated surface.

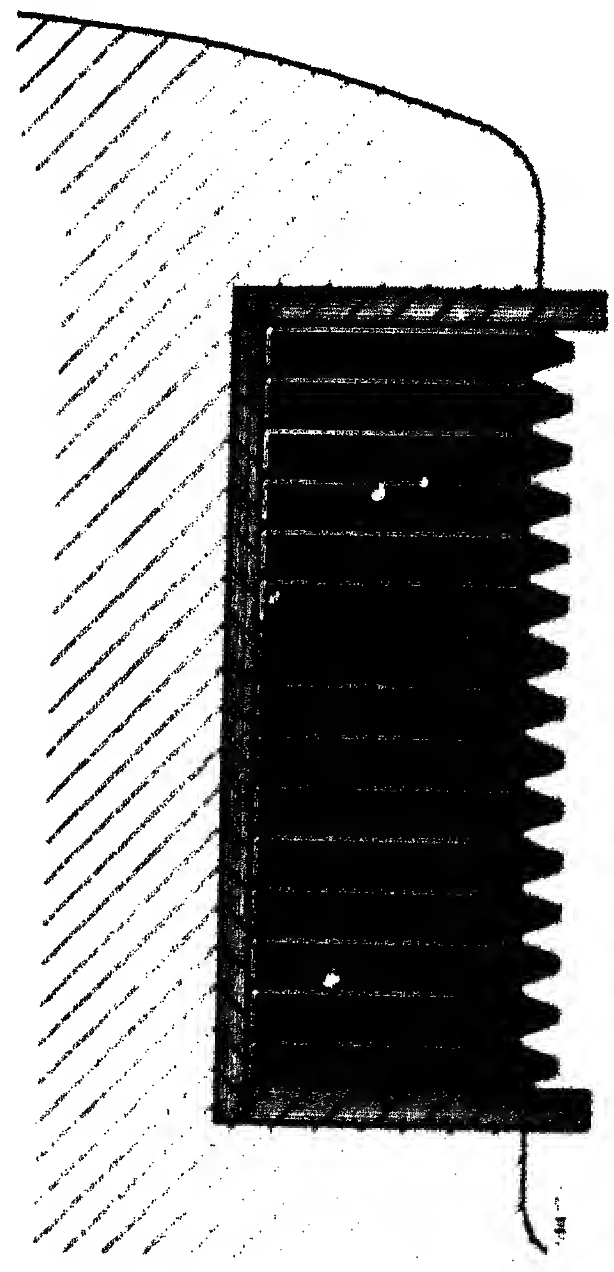


Fig. 53. Section through rotor coil, showing corrugated surface for cooling purposes.

The coils are insulated from the poles and from the pole wheel by sheets of presspahn or, in special cases by the use of asbestos. When the speed and axial length of the rotor are great, supports are fitted between the coils to prevent them from bulging outwards under the action of centrifugal force. This precaution is particularly necessary when the number of poles is small (see Fig. 33 and 47).

The coils of a rotor are as a rule connected in series, the actual connections between the coils being made by soldering, or, when the copper strip is sufficiently massive, by means of small bolts.

The rotor winding is connected to the slip rings by insulated copper cable or copper rods, which lie along the pole wheel or shaft and are fixed at suitable intervals.

THE SLIP RINGS

The slip rings themselves are one-piece steel forgings, or, for the larger sizes, steel castings, which are shrunk on to a cast-iron boss from which they are separated by a ring of micanite insulation.

In certain special cases, when changing the slip rings would involve the removal of heavy machine parts, the rings are made in two sections.

The excitation current passes to the slip rings through carbon brushes, and the design is such that the brushes can be used practically until the end, a constant pressure on the slip rings being maintained throughout.

The slip rings and brush gear of alternators with horizontal shafts are situated between the rotor and the bearing at the exciter end, the brush carrier usually being fixed to the bearing itself. The brush carrier of large slow-speed machines is independent of the bearings and fixed to the bedplate.

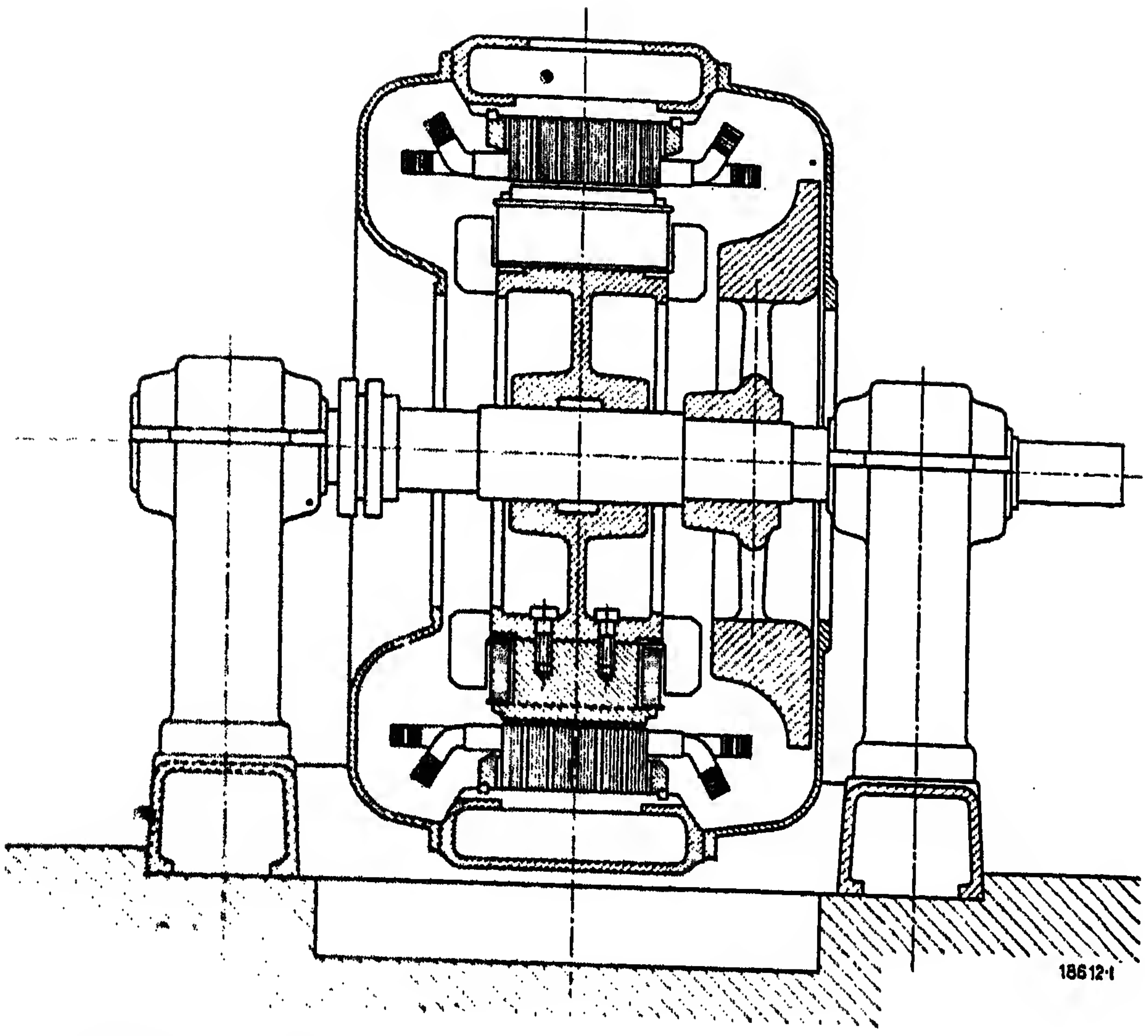


Fig. 54. Section through a three-phase alternator, showing flywheel.

The slip rings of machines with vertical shafts are usually fitted below the rotor, between it and the guide bearing. In exceptional cases they are placed on the upper end of the shaft above the thrust bearing or the exciter, the excitation leads passing through the hollow shaft. The position of the slip rings is always chosen with regard to accessibility for inspection and attendance.

FLYWHEEL EFFECT

The flywheel effect or moment of gyration as understood generally on the continent is WD^2 where W is the weight of the rotating body and D the diameter of gyration. In English speaking countries the flywheel effect is generally expressed as WR^2, where W is the weight of the rotating mass and R the radius of gyration.

If WR^2 be expressed in lb. ft^2 and it is desired to obtain the corresponding value as WD^2 in kg m^2, the value as given in lb. ft^2 is to be divided by 6.

To correct any false impressions, examples of which frequently occur in practice, it should be noted, that the magnitude of the flywheel effect is dependent solely on the degree of speed regulation required in the prime mover, i. e., in this case, the water turbine. The characteristics of the electrical generator in no way influence it.

Hence when requesting tenders for plant, the turbine builder should always be asked first to specify the flywheel effect required for the turbine; this information must be available before an offer for a generator can be prepared.

Every rotor size has a definite flywheel effect or moment of gyration. With the exception of small high-speed alternators, this normal value can be increased to a certain extent if parallel operation or the conditions of regulation require it. The means adopted for this purpose depend upon the type and diameter of the rotor.

With rotors of large diameter, it is usually possible to increase the flywheel effect or moment of gyration to the necessary extent by providing a heavier rim; when the diameter is small, a cast-steel flywheel can be placed on

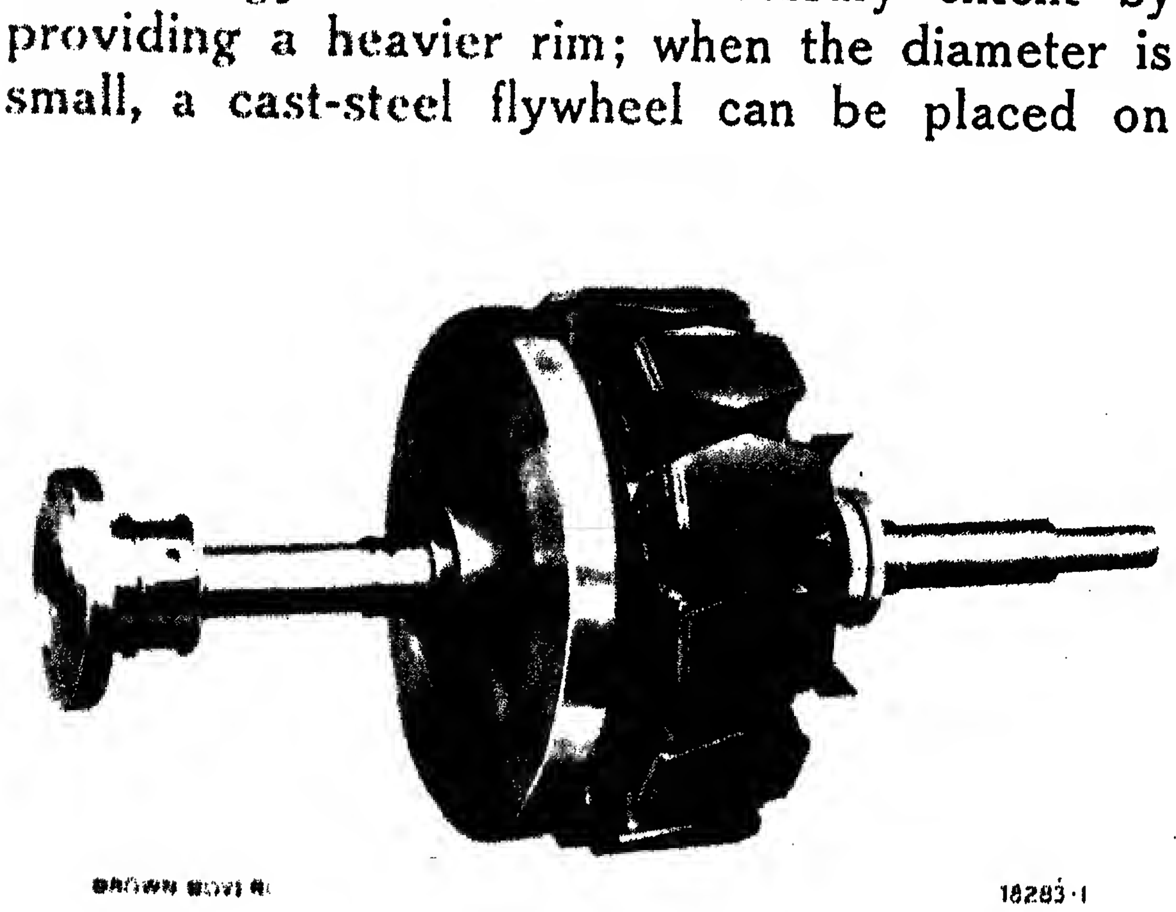


Fig. 55. Rotor with flywheel for a three-phase alternator, 305 kVA, 500 r. p. m.

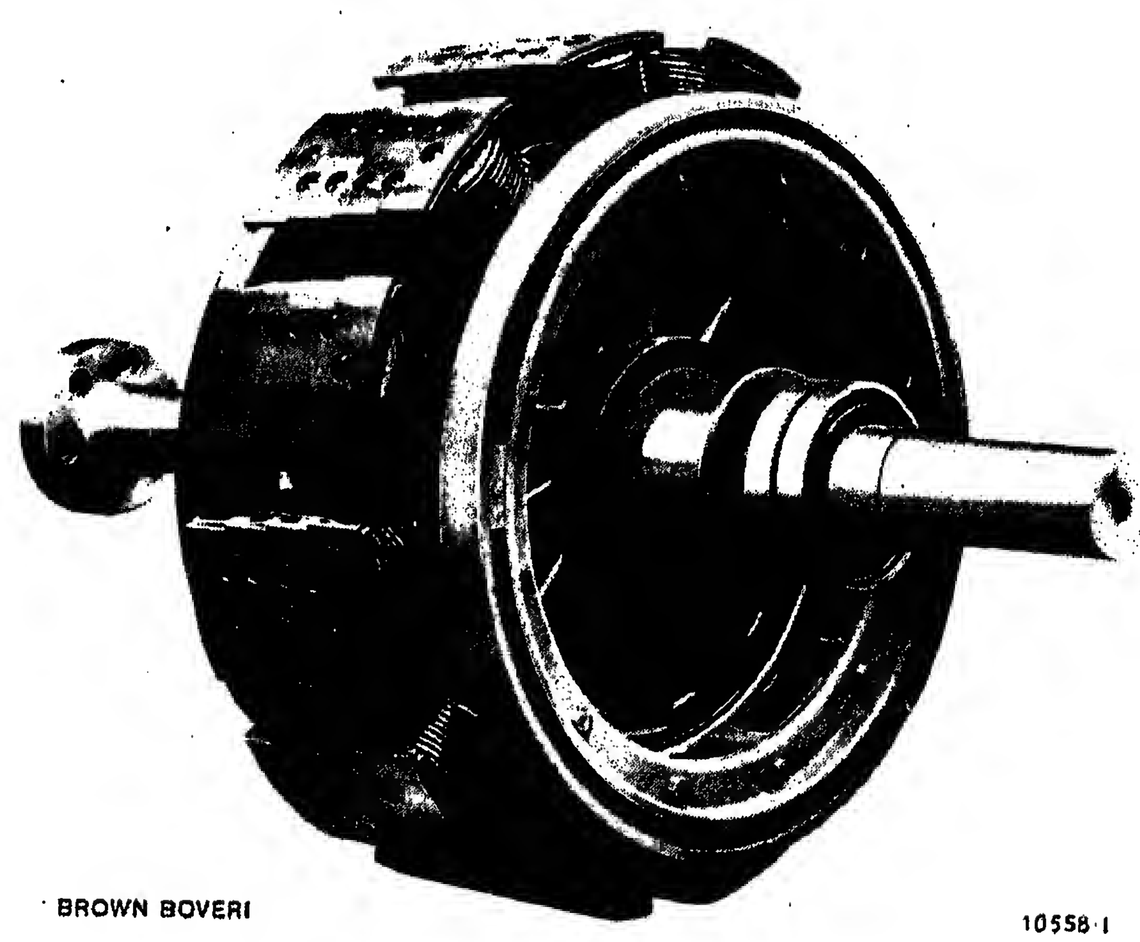


Fig. 56. Rotor and flywheel for a three-phase alternator, 4750 kVA, 500 r. p. m.

the shaft next to the rotor (Figs. 54 and 55), or a cast-steel ring either on one, or on both sides (Fig. 56). If the flywheel effect is still insufficient, a special flywheel must be provided outside the machine itself (Figs. 57 and 87).

THE OVER-SPEED TEST

When constructing machines to be driven by water turbines, account must always be taken of the fact that, should the speed governor fail to act, the speed can rise considerably above the normal value. As a rule, the runaway speed is taken as 1·8 times the normal; with the modern high-speed turbines, however, it can increase to 2—2·5 times normal or even more. As the stresses increase as the square of the speed, these high speeds make very exacting demands upon the material and the construction, and it is therefore of the greatest importance that the designer of the alternator should be furnished, by the turbine builder, with particulars of the runaway speed in each individual case. The necessary reliability is secured by careful choice of the most suitable type and of the materials employed, together with accurate calculation of the stresses to be anticipated should the turbine run away. The selection must be such that the stresses are considerably below the elastic limit of the materials employed. It is consequently necessary to apply the most exacting tests; these are of two kinds as follows:—

1. Specimens are taken from different parts of the rotor and their strength thoroughly tested in the materials laboratory. Further, each part is carefully examined during machining for any defects such as cracks or blow holes.
2. After the rotor has been completely assembled, it is subjected to an over-speed test at the runaway speed of the turbine to which it is to be coupled; at this speed, there must be no permanent or dangerous deformation of any part of the rotor, particularly of the rotor windings, which after the over-speed test are subjected to a further insulation test.

Every rotor is balanced statically, and, when necessary, also dynamically; if desirable this test is also repeated after the over-speed test, in order to ensure that the rotor will run smoothly and without vibration.

THE SHAFT

The shaft is of wrought Siemens-Martin steel and is substantially proportioned to ensure a small deflection. Heavy shafts are annealed after forging or after rough turning, in order to relieve forging stresses, and bored out in an axial direction to enable the quality and uniformity of the material to be checked. Specimens for material tests are taken from suitable places to ascertain whether the material is of the necessary quality. When this is not practicable, the Brinell test is substituted.

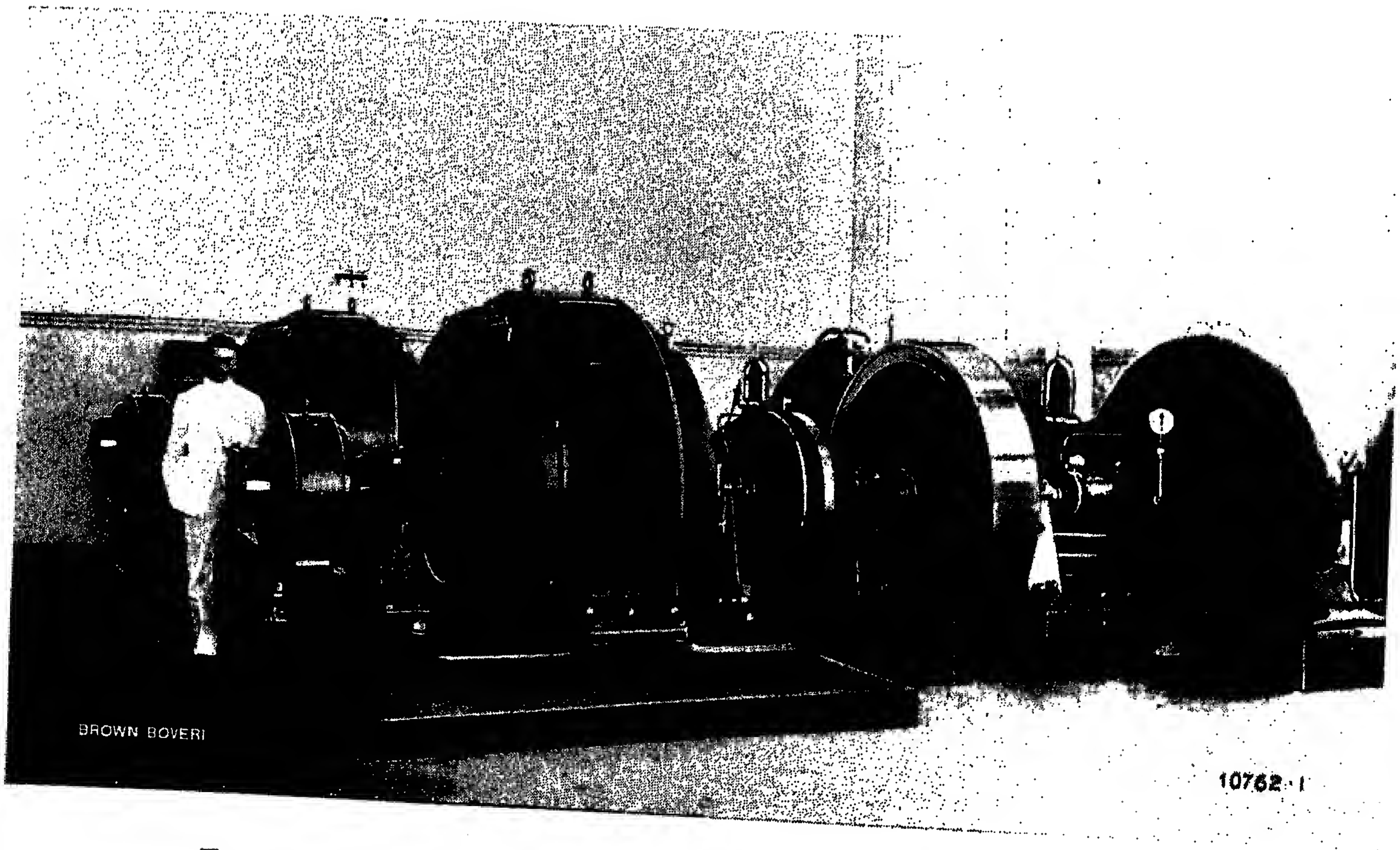


Fig. 57. Two three-phase alternators, each 600 kVA, 6300 V, 50 cycles, 750 r. p. m., installed in the Tjato Valley Central Station in Java.

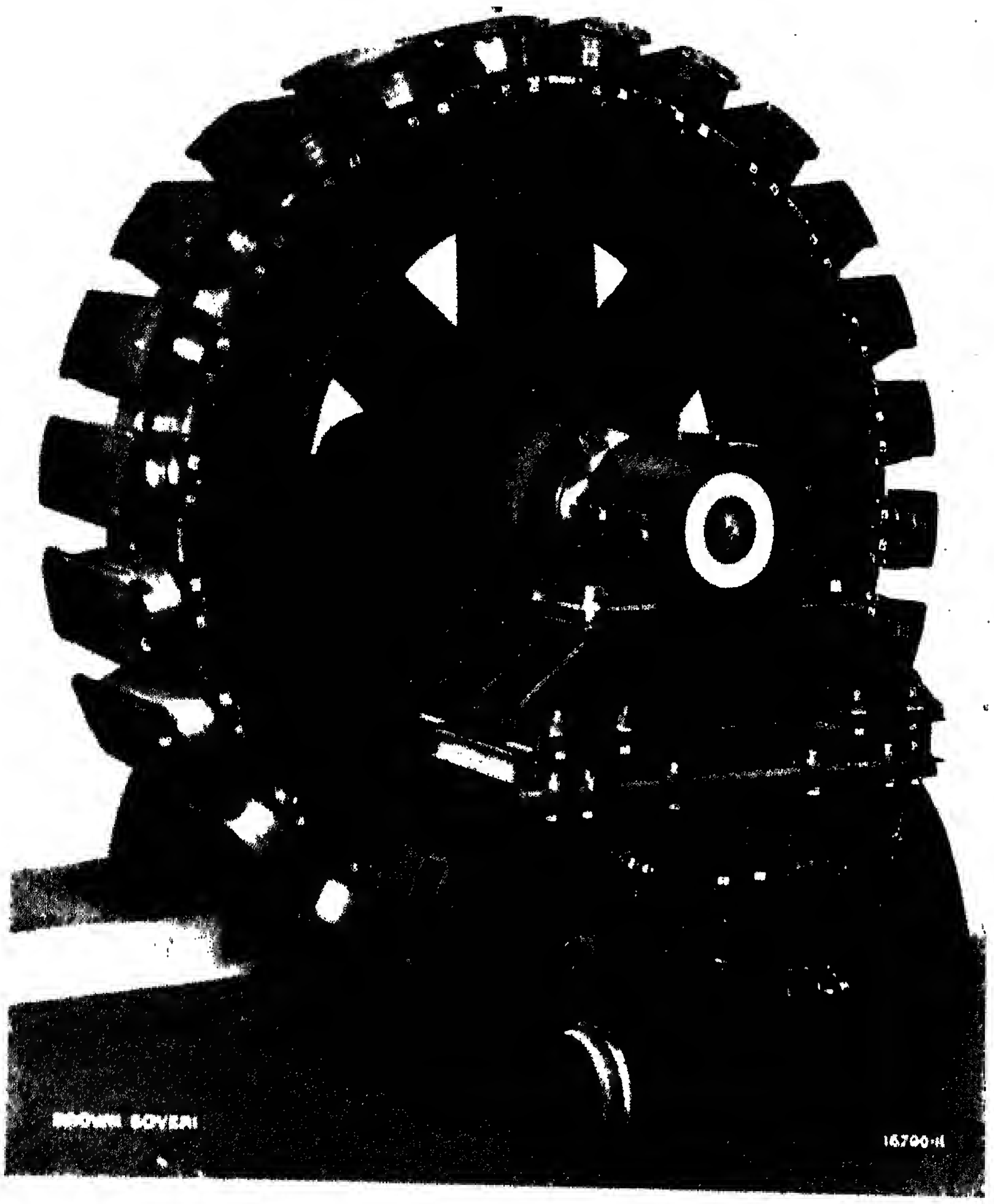


Fig. 58. Finished pole wheel of a three-phase alternator, 12,500 kVA, 500 r. p. m., mounted on special truck for transit to the over-speed test bed.

Part of the five alternators of the Eguzon Power Station of the S. A. Union Hydro-Electrique.

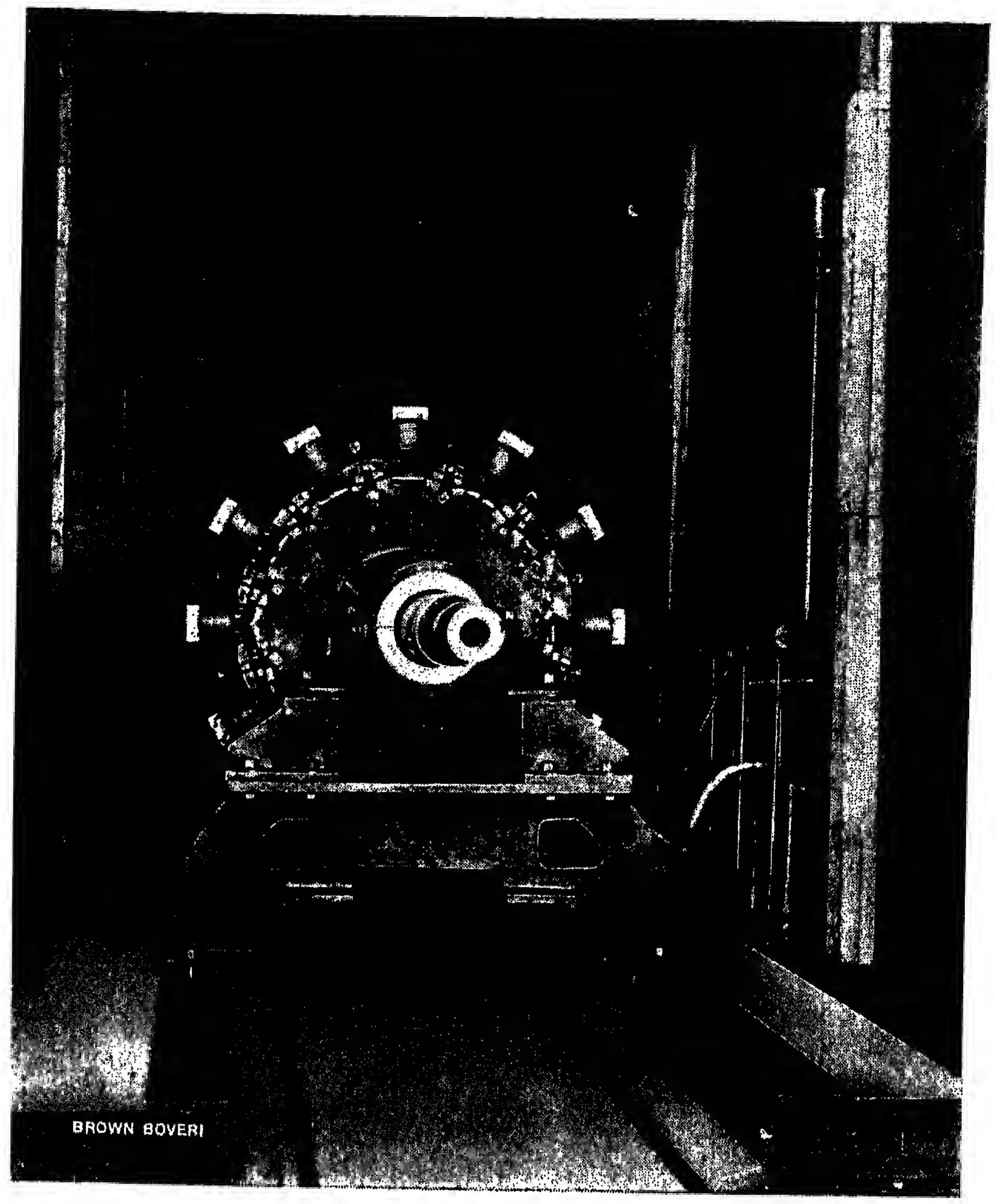


Fig. 59. Finished rotor of a three-phase alternator, 16,500 kVA, 500 r. p. m., for balance testing on the over-speed test bed.

Part of the four alternators in the Rempen Power Station of the Wäggital Power Supply Co.

THE BEARINGS

Ring lubrication is always provided when the shaft is horizontal, each bearing having as a rule two rings, an oil-level indicator and a drain cock. One-piece bushes are only fitted to small machines of the bearing-bracket type; in all other cases they are in two parts and consist of a cast-iron shell lined with white metal. For higher speeds, or when the load on the bearing is greater so that natural cooling is inadequate, the bearings are water cooled. For this purpose the cooling water

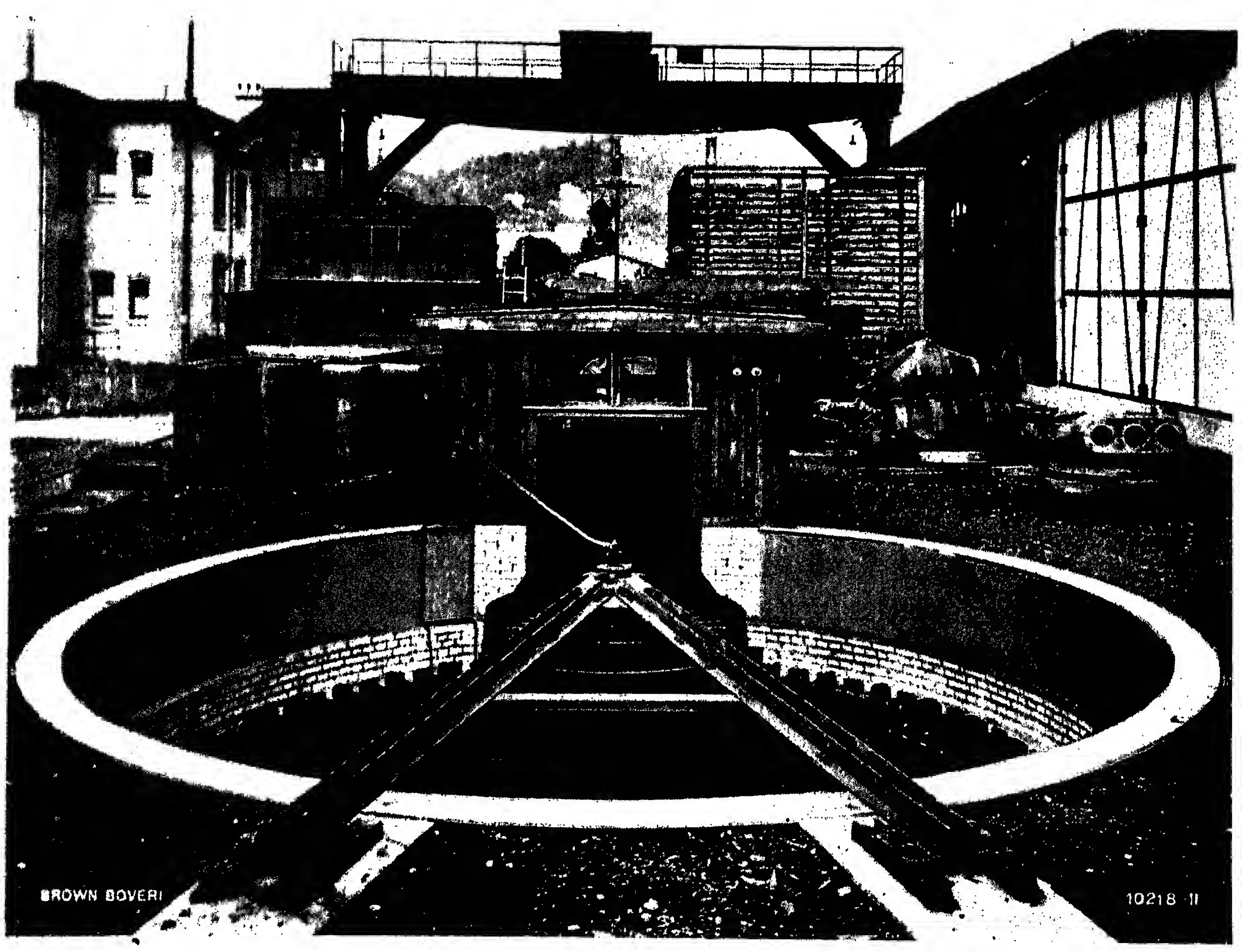


Fig. 60. Finished rotor of a three-phase alternator, 7050 kVA, 83·3 r. p. m., on the over-speed test bed for balancing machines of large diameter.

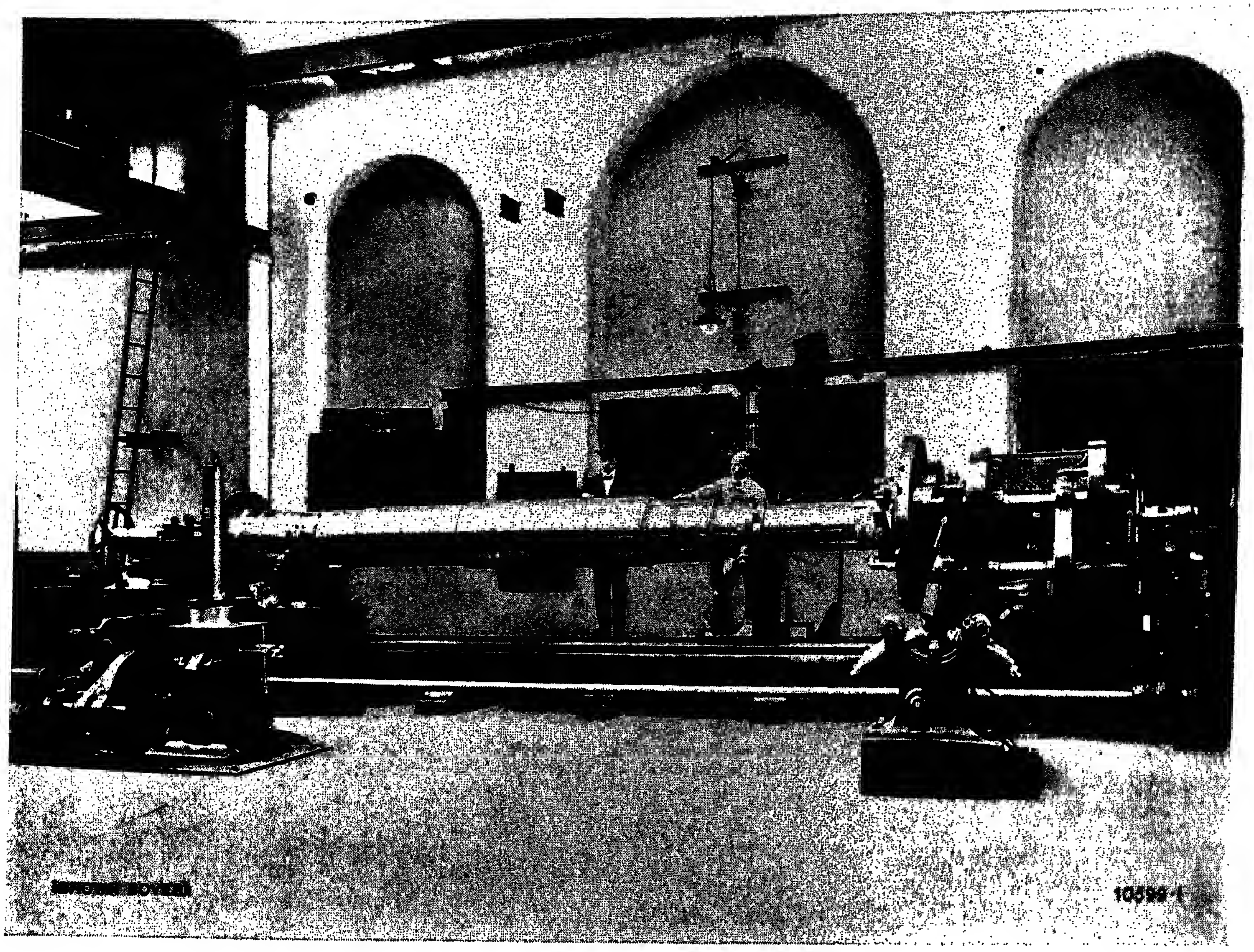


Fig. 61. Finishing a heavy shaft for a single-phase alternator, 9000 kVA, 333 r. p. m.

flows through spirals of copper tubing embedded in the white-metal lining of the lower half of the bearing. To indicate to the attendant that no interruption has occured in the flow, and to enable the rate of flow to be adjusted, each bearing is provided with a water cock and a funnel, on the outlet side. The necessary cooling-water volume is small, and for a bearing of a 200-mm shaft running at 1000 r. p. m., for example, it amounts to only about 8 litres per minute.

The bearings of vertical-shaft machines are lubricated by a small gear pump driven either directly by the generator shaft, or through a belt from the governor shaft of the turbine. The oil flows through both bearings in succession, and between the pump and the bearings, gauge glasses and valves are placed in the pipe line to enable the flow of oil to be inspected and regulated if necessary. Water cooling is usually unnecessary for the bearings of machines with vertical shafts.

Under certain conditions, depending upon the number of poles and the distribution of the stator laminations, currents may be generated in the shaft and flow through the bearings and stator frame or bedplate. These currents can give rise to corrosion of the bearings, and, in order to prevent this, the bearing pedestal at the end of horizontal-shaft alternators remote from the drive, and the shell of the upper bearing of vertical-shaft alternators are insulated by inserting sheets of presspahn or micanite; in the event of the bearing being water-cooled, the cooling water pipes are also insulated.

THE THRUST BEARING

One of the most important components of machines with vertical shafts is the thrust bearing, which has to carry the weight of the rotating parts of both alternator and turbine, together with the hydraulic thrust on the latter — a load which, with large units, may amount to a hundred tons or more.

Brown, Boveri & Co. make thrust bearings of two types for this purpose. For moderate loads and low speeds the design shown in Fig. 64 is suitable, in which the running surfaces are of cast iron, in one piece and spherically seated. Bearings of numerous types all on this principle have been in use for very many years without giving rise to the slightest trouble. Each bearing is provided with an oil gauge and drain cock. The spherical seating upon which the lower half rests makes it to some extent self-adjusting. The whole bearing runs in an oil bath and is cooled when necessary by cooling-water spirals incorporated in the bearing itself.

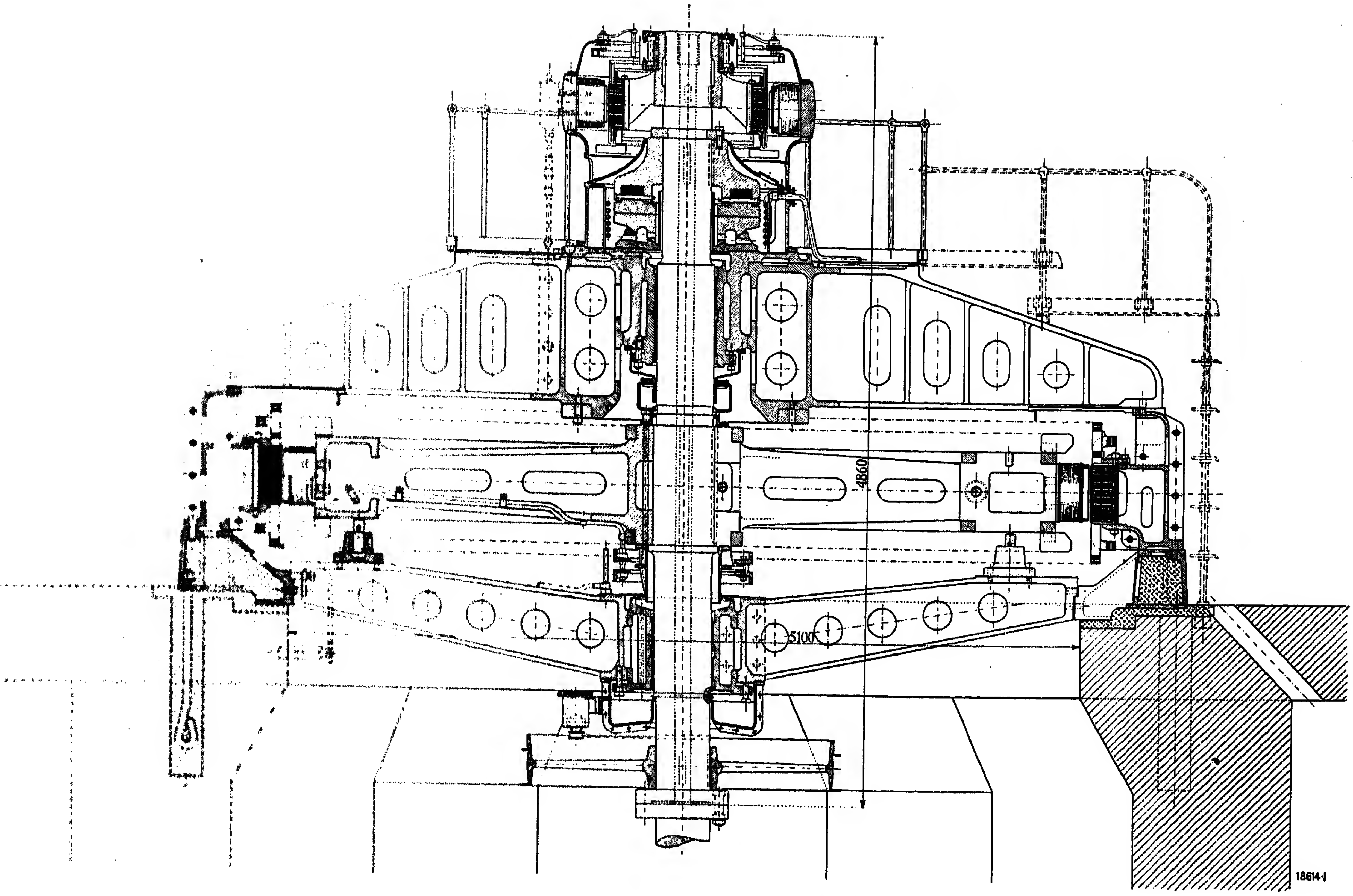
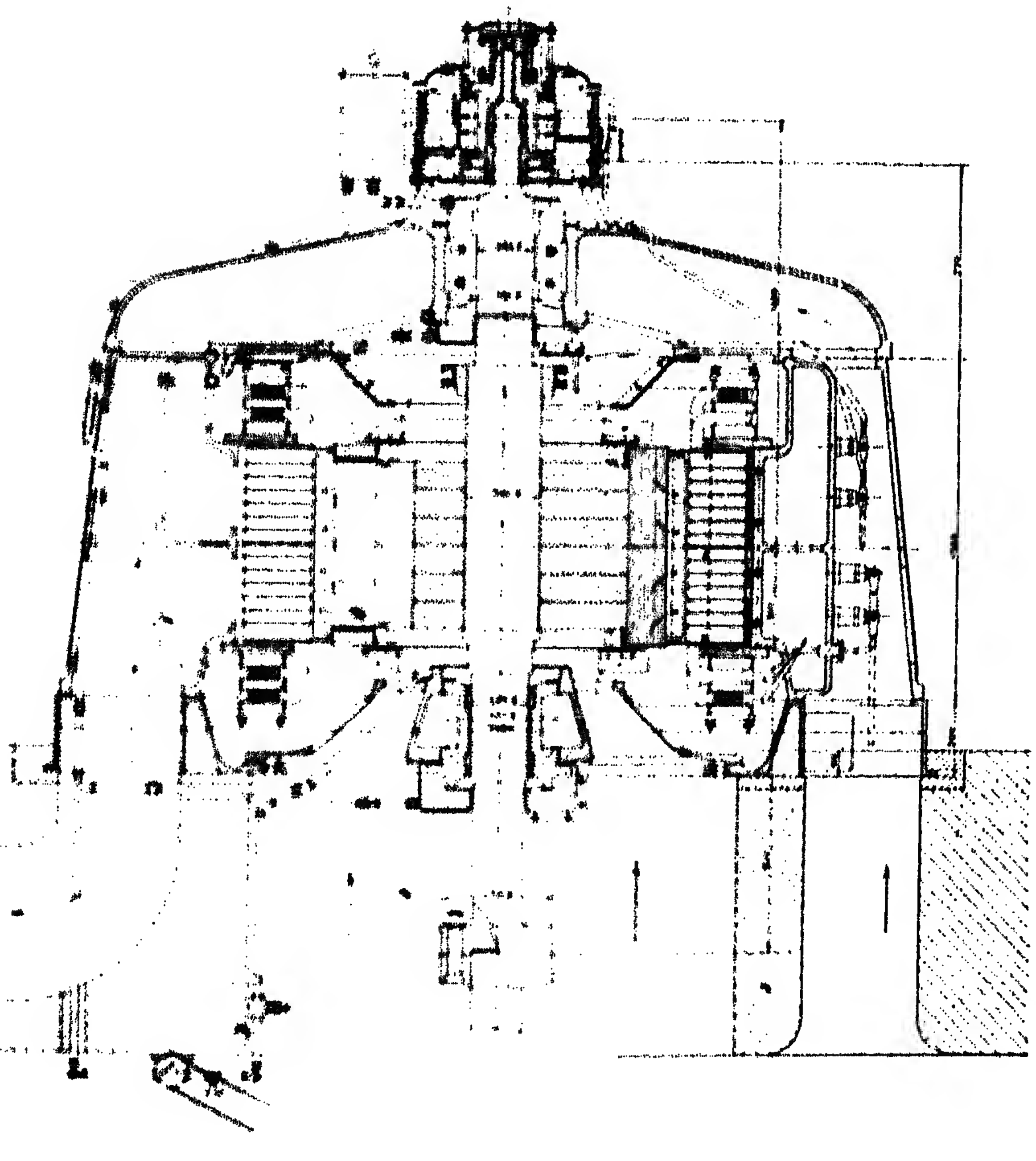


Fig. 62. Section through a vertical-shaft, three-phase alternator, 2200 kVA, 9500 V, 50 cycles, 107 r. p. m.
Four alternators of this type have been delivered to the Wynau Power Station of the Wynau-Langenthal Electrical Supply Co.



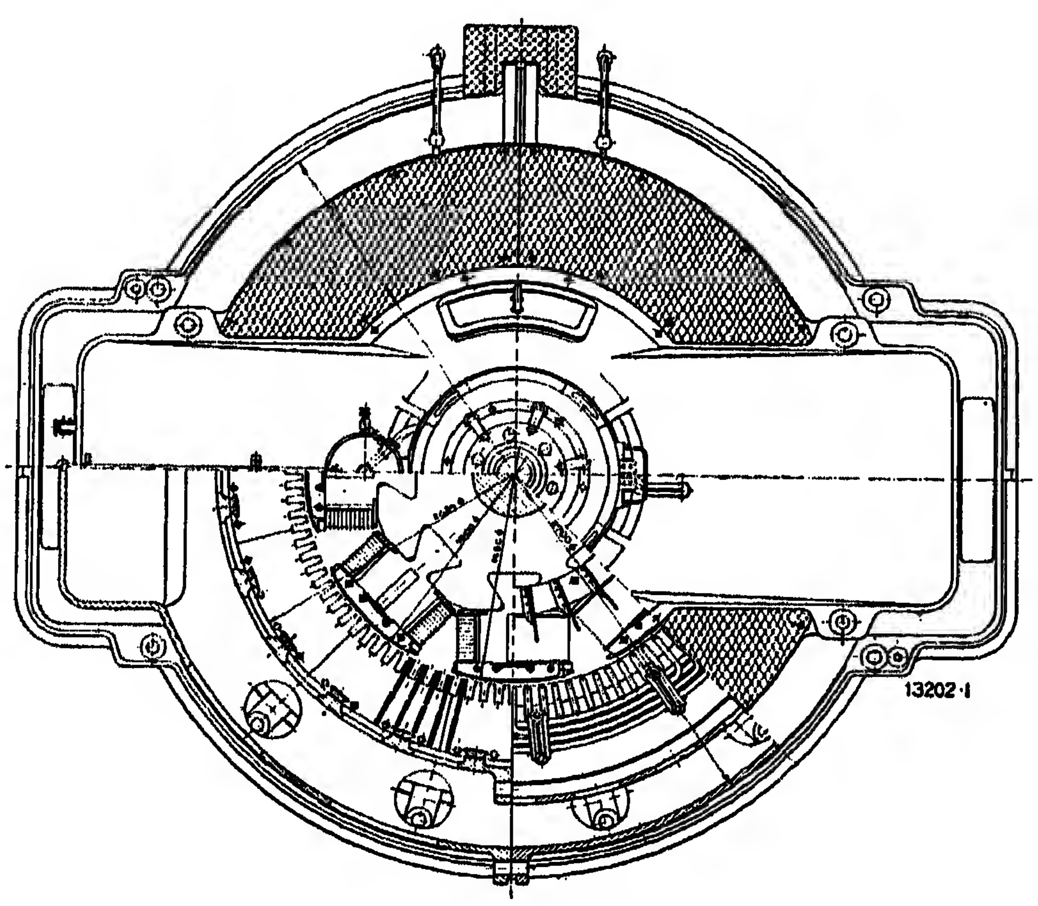


Fig. 63. Section through vertical-shaft, three-phase alternator, 3000 kVA, 5000 V, 50 cycles, 750 r. p. m.
Three such alternators have been supplied to the Buitreras Power Station of the Soc. Hidro-Electrica del Guadiaro, Seville.

As shown in Fig. 65, thrust bearings, which are used for thrusts up to 500 tons, and in Fig. 66 for high speeds, have the usual one-piece bearing surface replaced by a number of separately pivoted segments. The theoretical investigation and practical research carried out upon bearings of this kind are dealt with in detail in the Revue BBC, 1917, Nos. 1—4. The segments are supported somewhat eccentrically and when the shaft is running take up such a position that a wedge-shaped oil film forms between each segment and the surface of the thrust collar on the shaft. In this way, contact of the surface is prevented and friction losses are extremely small.

It is very important that the load should be uniformly distributed between the segments. This is accomplished in a most effective manner by supporting the segments upon steel balls as shown in Fig. 65.

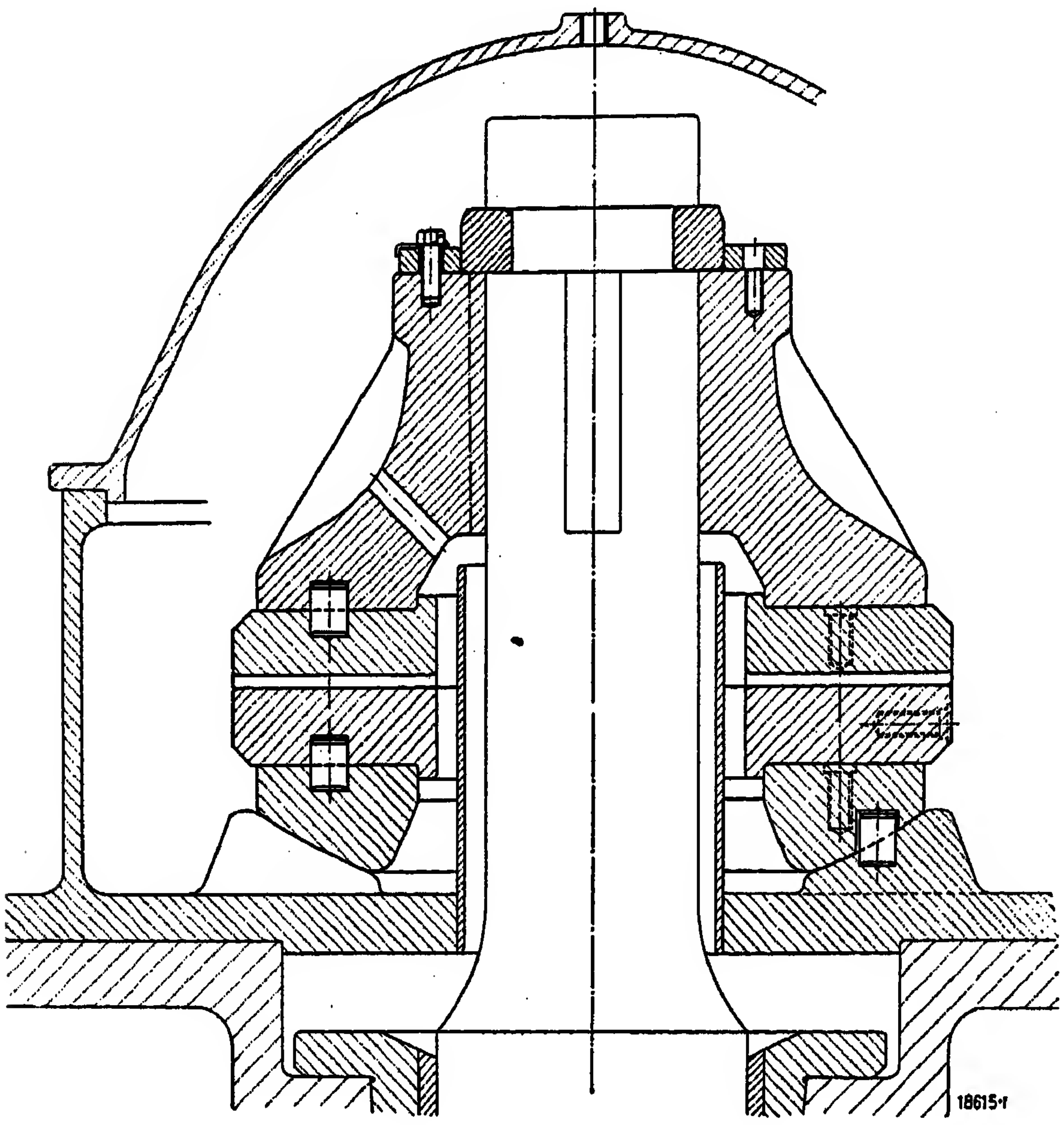


Fig. 64. Section through a thrust bearing, 40 tons bearing pressure, 94 r. p. m.

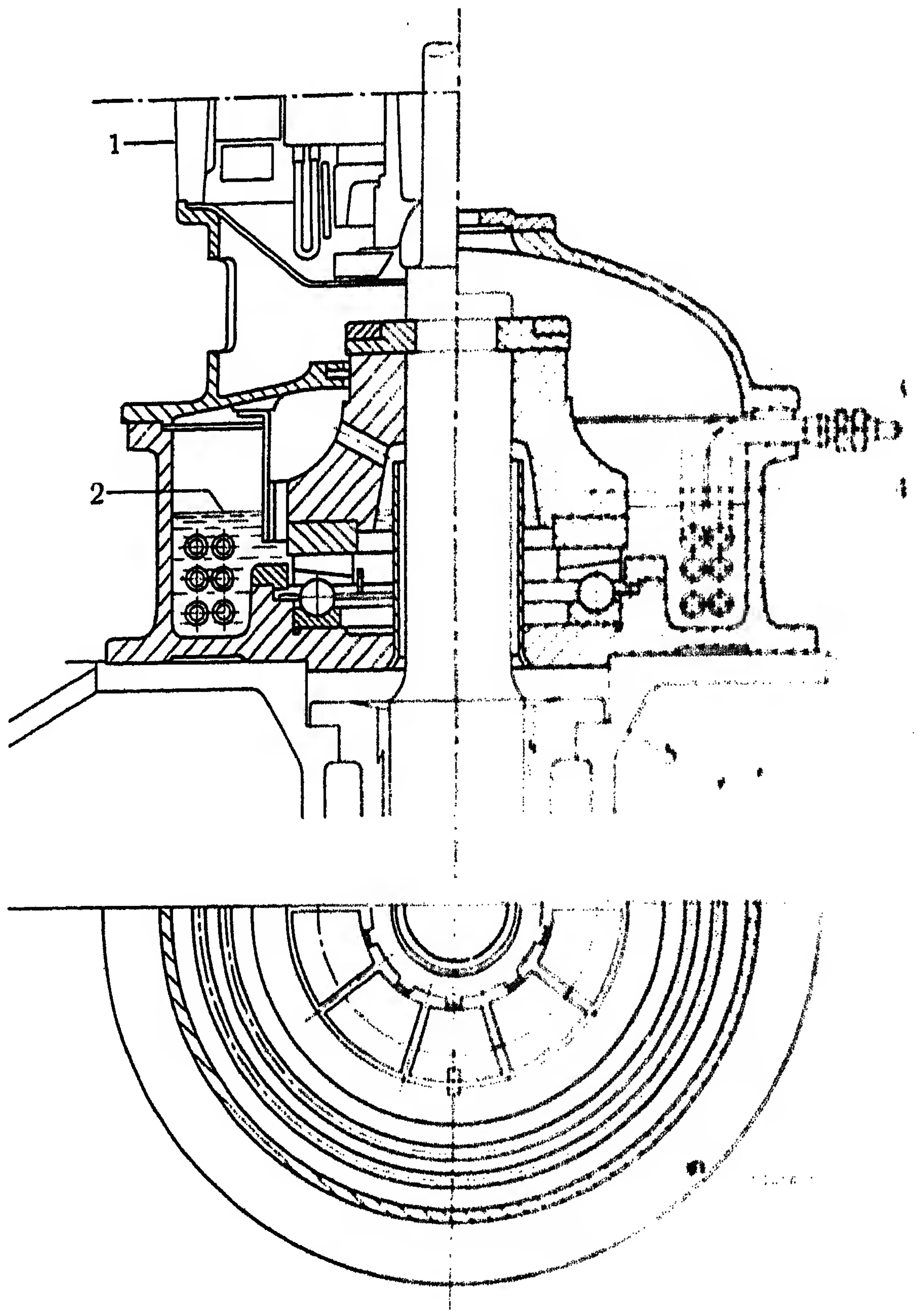


Fig. 65. Segmental thrust bearing, 350 tons bearing pressure, 100 r. p. m.
1. Excitation machine. 2. Oil well. 3. Cooling water 4. Thrust bearing. 5. Alternator.

Tests have shown that bearings of this kind are capable of withstanding bearing pressures up to 500 kg/cm² and over; normally, however, they are not loaded beyond 20—30 kg/cm² and a number of different designs have shown that bearings so dimensioned are completely reliable under the most unfavourable conditions, even at low speeds such as occur during starting and slowing down.

At the time of writing, Brown Boveri segmental thrust bearings for four 16,500-kVA three-phase alternators for the Rempen Power Station of the Wäggital Power Supply Co. are under construction (Fig. 66). In this instance, the total load amounts to about 70 tons at a rated speed of 500 r. p. m. and a runaway speed of 1050 r. p. m.

For the purpose of taking the load off the thrust bearing for inspection or repairs, the lower bearing bracket is provided with supporting bolts (see Figs. 62 and 66), upon which the rotor can rest after it has been raised by means of the crane.

THE BRAKES

On account of the importance of sparing the thrust bearings, especially those of large machines, as much as possible, it is often desirable to lessen the time taken for the machine to slow down. For this purpose, a brake is provided, which, if it cannot be combined with the turbine, is incorporated in the alternator. This brake consists of a number of brake blocks applied by compressed air, either to the rim of the rotor itself, or to a special brake drum mounted on the rotor, see Fig. 67. Compressed air may be employed with advantage for this purpose, as it is always necessary for other purposes in large power stations, e. g., the cleaning of machines and apparatus, and an air-compressor plant, either stationary or portable may usually be assumed to exist. There is, naturally, no reason why the brakes should not be actuated by some other means such as oil or hydraulic pressure.

The use of the brake gives rise to dust, and there is the danger that this dust may be drawn into the rotor and forced into the windings. It is consequently advisable, only in cases of emergency, to apply the brake when the machine is running at full speed, the machine being brought to rest within a few minutes. Normally, however, the brake should not be used until the speed has become low enough to spare the thrust bearing; e. g. only when the speed has dropped to $1/3$ - $1/4$ of the normal.

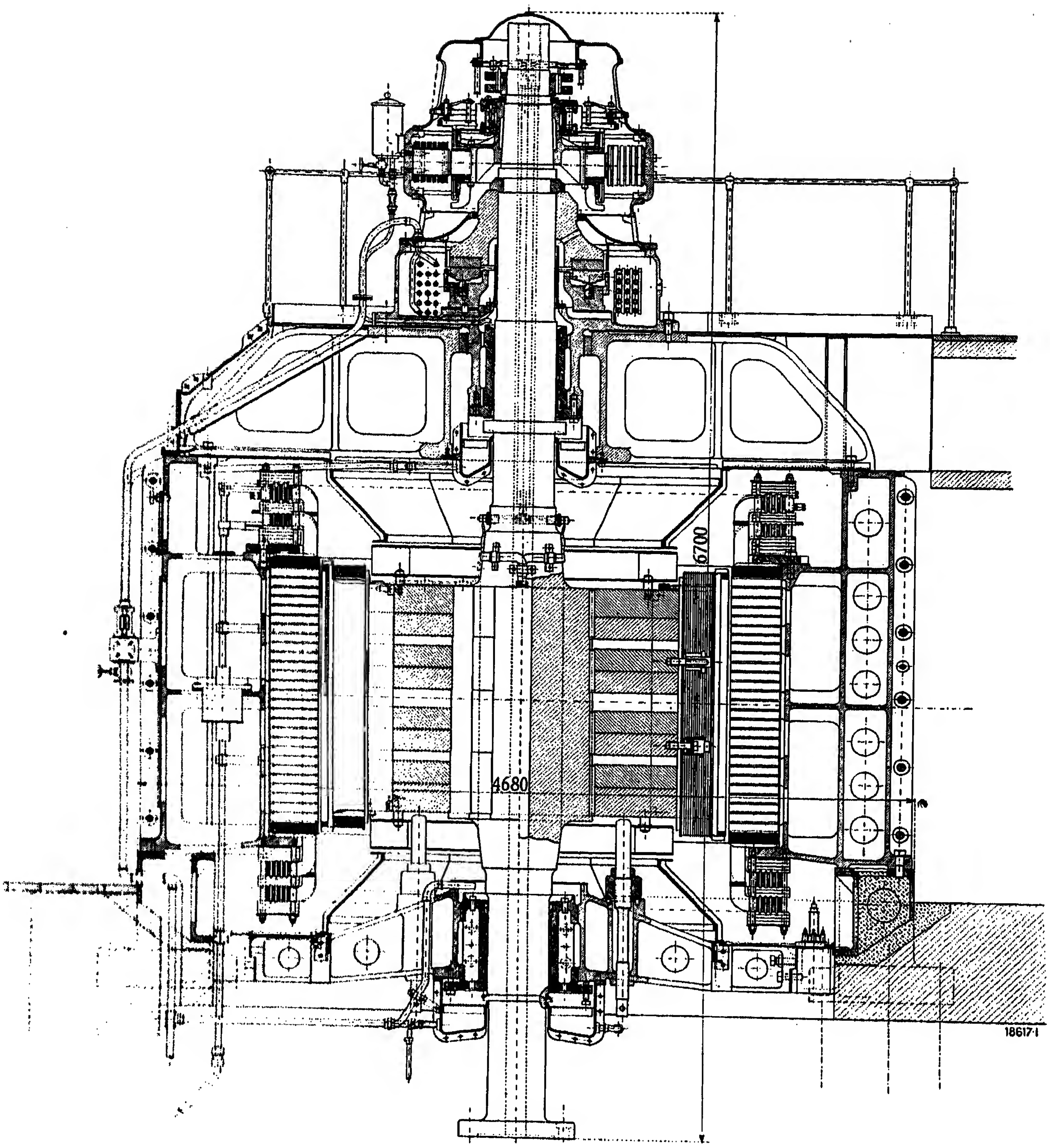


Fig. 66. Section through a three-phase alternator, 16,500 kVA, 8800 V, 0·8 power factor, 50 cycles, 500 r. p. m.

Four alternators of this type have been supplied to the Rempen Power Station of the Wäggital Power Supply Co.

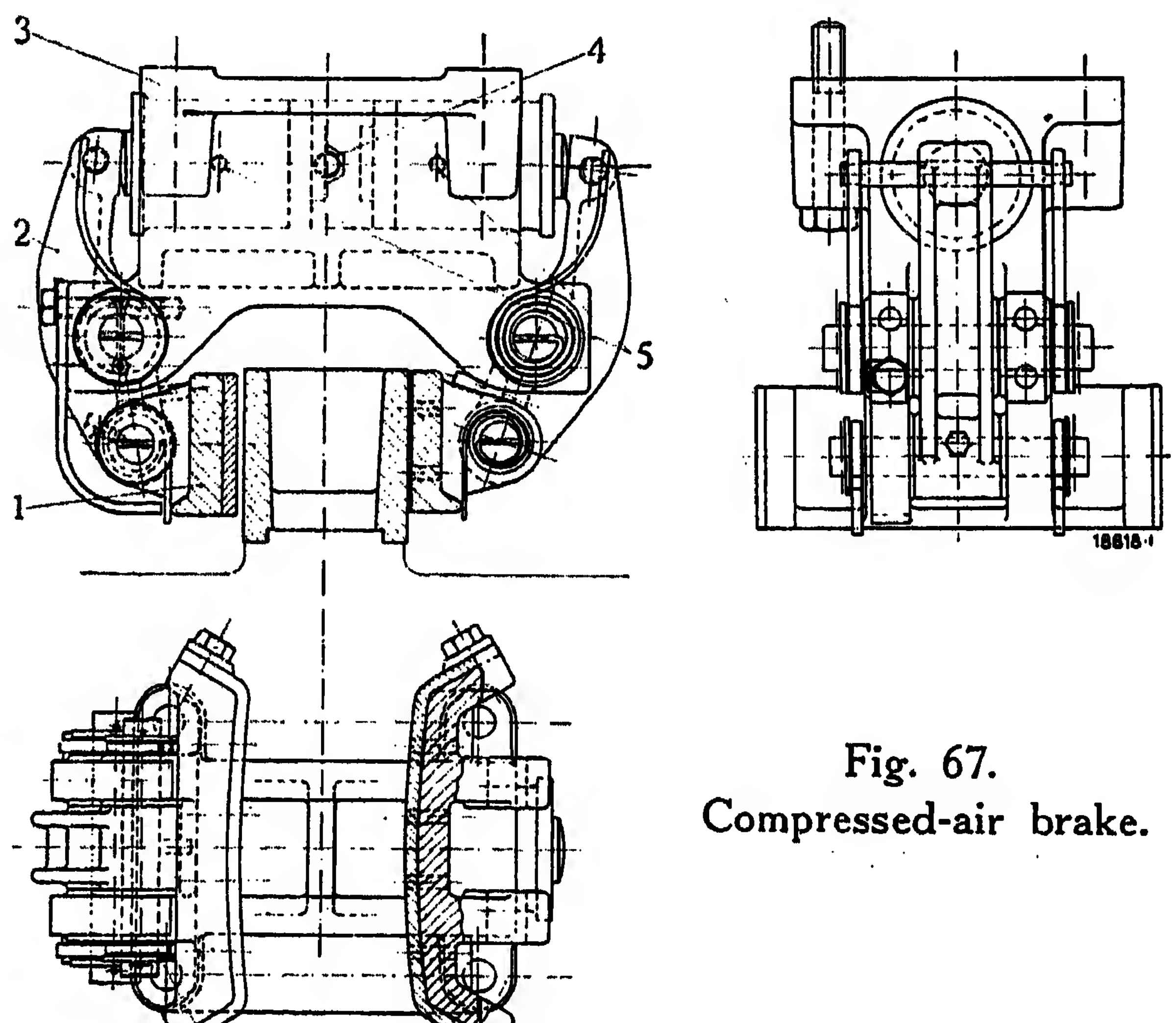


Fig. 67.
Compressed-air brake.

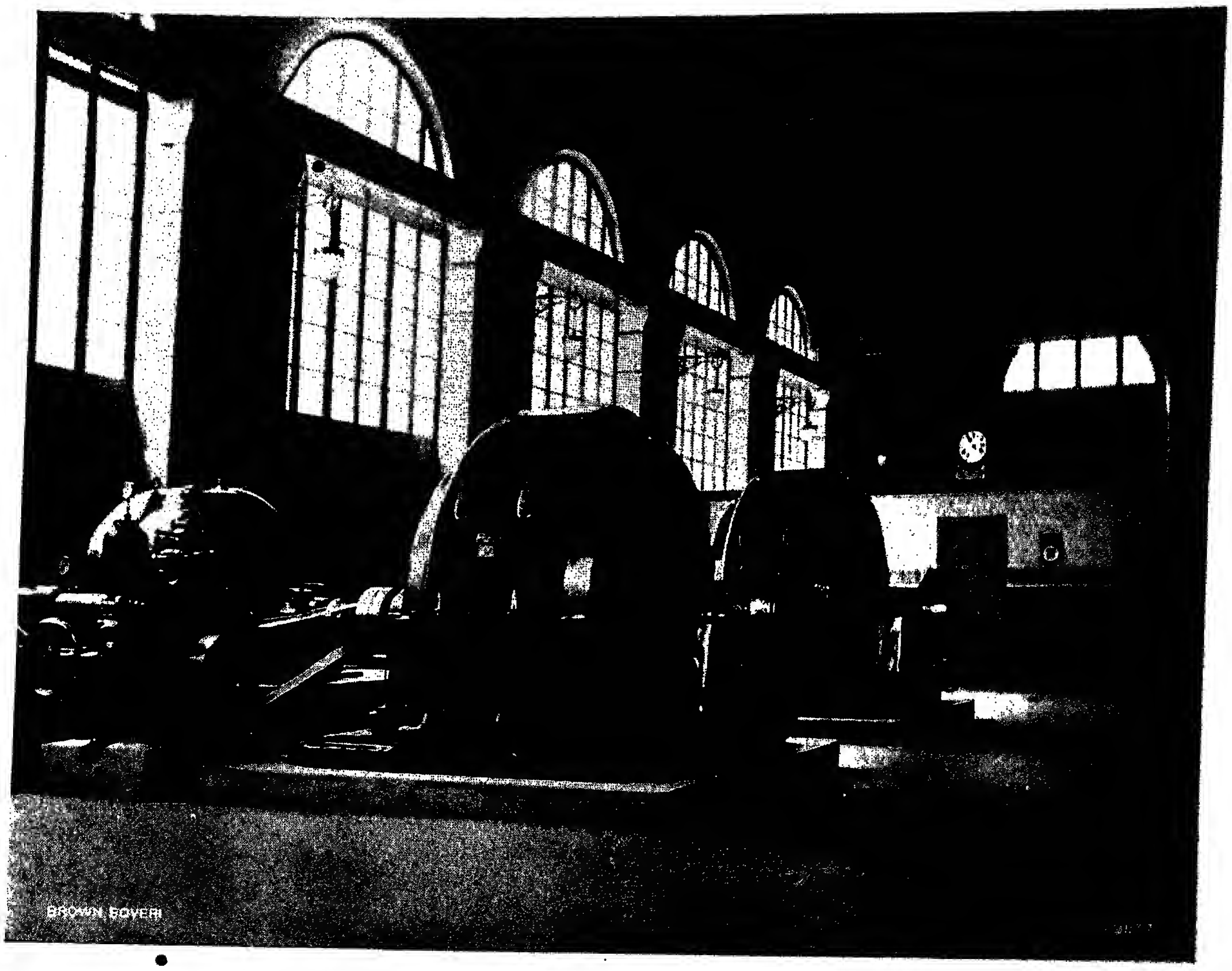


Fig. 68. Somiedo Power Station of the Hidro-Electrica del Cantabrico.
Two three-phase alternators, each 3300 kVA, 5300 V, 50 cycles, 600 r. p. m., are installed.

INHERENT REGULATION

The inherent regulation of an alternator is the percentage rise in pressure which occurs when the rated full-load is thrown off and the machine runs on no-load, the speed and excitation remaining unchanged. The low values, previously usual, of 6–8 % at unity power factor and 15–20 % at a power factor of 0·8 are to-day considered unnecessary, and machines with poorer inherent regulation of about 15 to 30 % at unity power factor and 30–50 % at a power factor of 0·8, according to the output, are coming into favour. The current of such machines in the event of sudden short circuit is relatively small — an absolutely essential property for the protection both of the machines themselves and also of the distribution system with

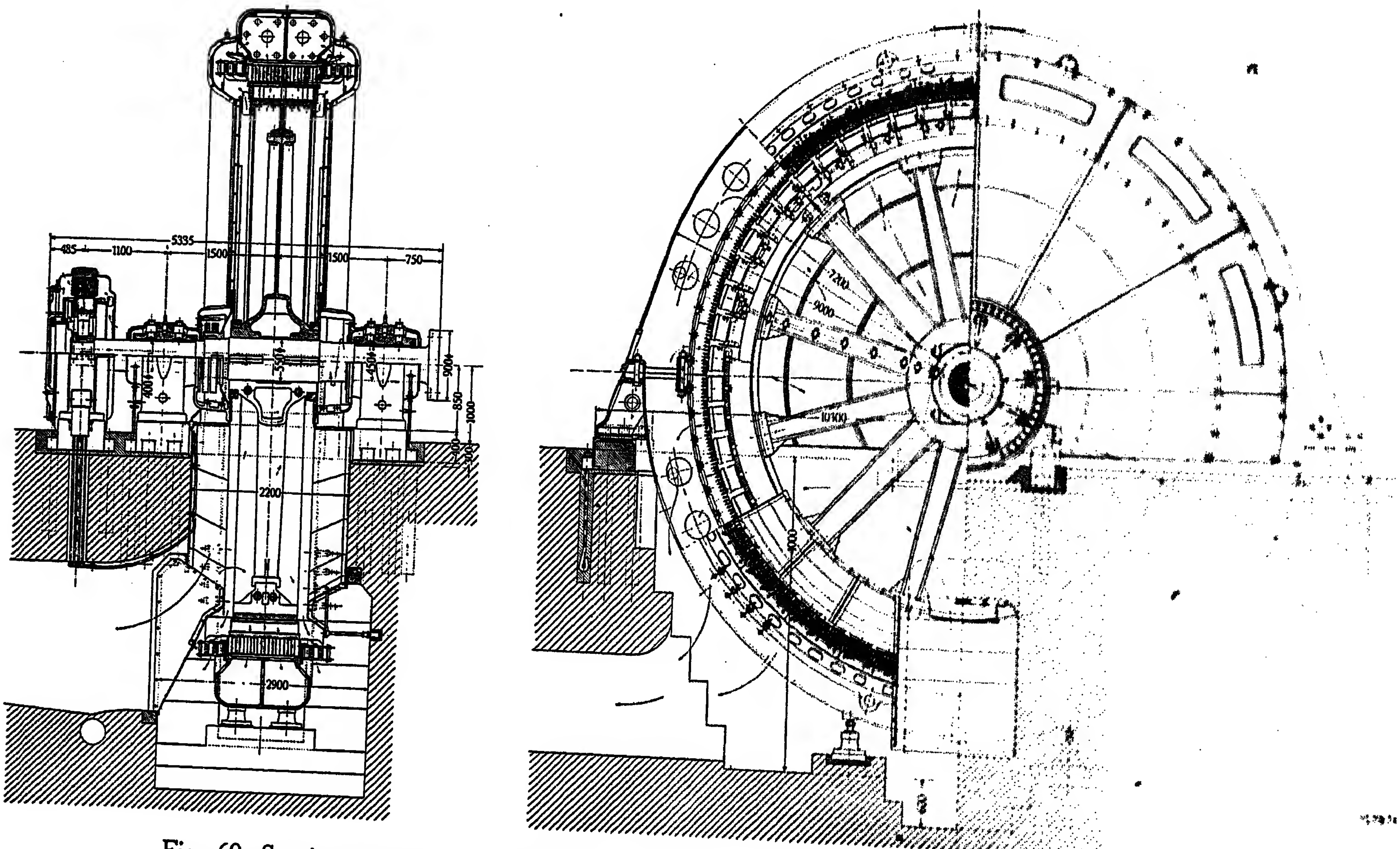


Fig. 69. Section through a three-phase alternator, 12,000 kVA, 7500 V, 50 cycles, 107 r. p. m.
Four such alternators have been supplied for the Raanaasfoss Central Station of the Akershus Power Supply Co., Norway.

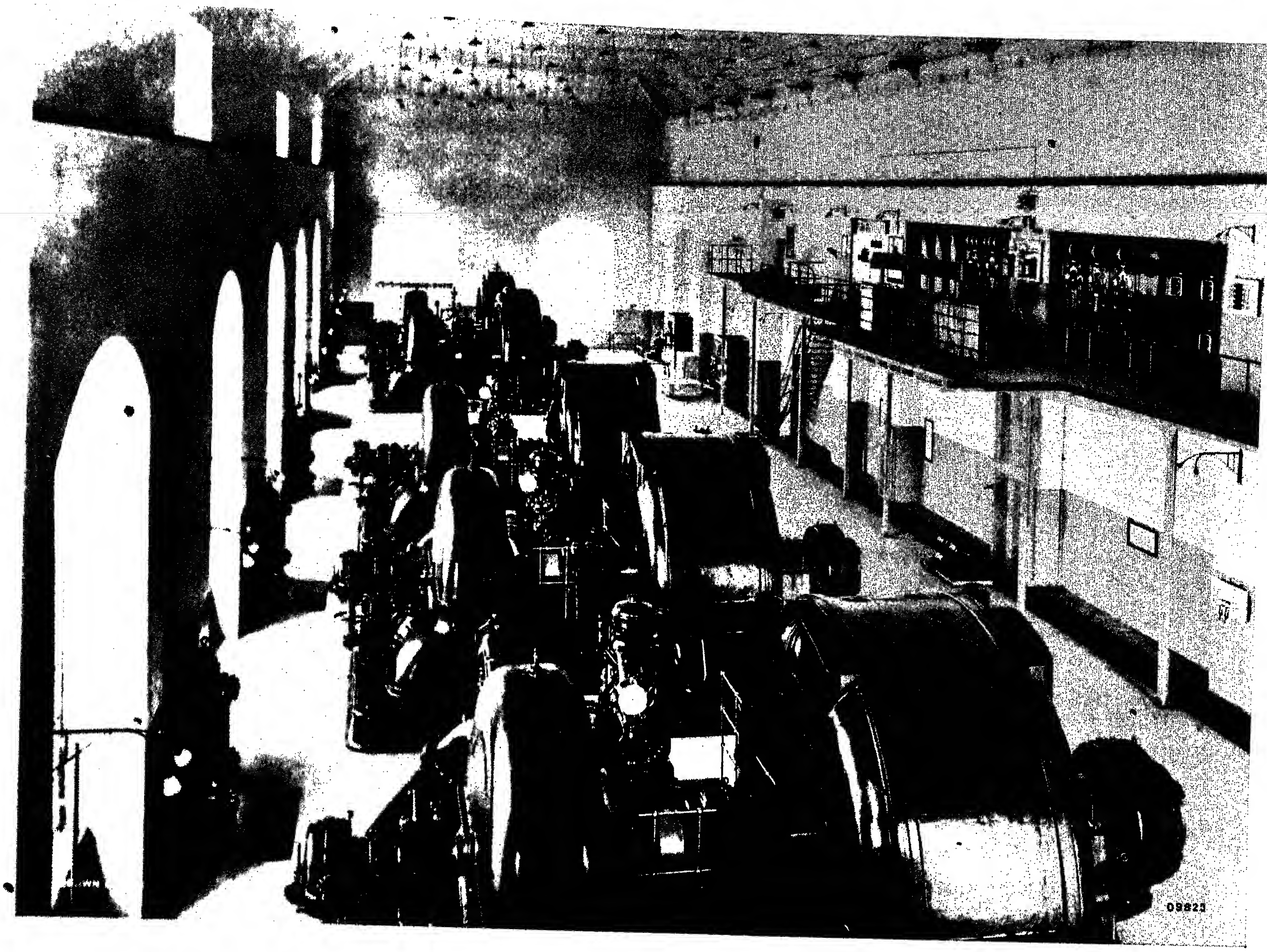


Fig. 70. The Power house of the Kandergrund Central Station of the Bernese Power Supply Co. Two three-phase alternators each 2750 kVA, 17,600 V, 40 cycles, 300 r. p. m. and three, single-phase alternators each 2700 kVA, 17,600 V, 16 ⅔ cycles, 333 r. p. m., are installed.

regard to the continual increase in the output of power stations. On the other hand, the Brown Boveri automatic quick-acting regulator, which has been developed to a very fine state, enables reliable and accurate regulation to be obtained even with alternators of which the inherent regulation is poor. The weight for a given output can be reduced and the efficiency greatly improved by permitting the use of machines with a poor inherent regulation.

WAVE FORM

The wave form is of very great importance; the voltage wave of alternators should be as nearly sinusoidal and free from harmonics as possible. A distorted voltage wave means increased losses, not in the alternator only, but also in the distribution system and the motors and converters connected to it; together with a greater liability to disturbances in the network. Fig. 71 shows the wave form of a Brown Boveri alternator.

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Fig. 71. Oscillogram of the pressure of a vertical-shaft, three-phase alternator on no-load, 8000 kVA, 17,600 V, 50 cycles, 167 r. p. m.

PARALLEL WORKING

Brown Boveri alternators are so designed and constructed that, when driven by water turbines, they run entirely without fluctuation of speed either independently or in parallel, the torque of water turbines being uniform, as opposed to the varying torque of reciprocating prime movers such as steam, gas, or Diesel engines. A hydro-electric set will generally operate quite satisfactorily in parallel with alternators driven by other means, as long as these are able to run in parallel among themselves.

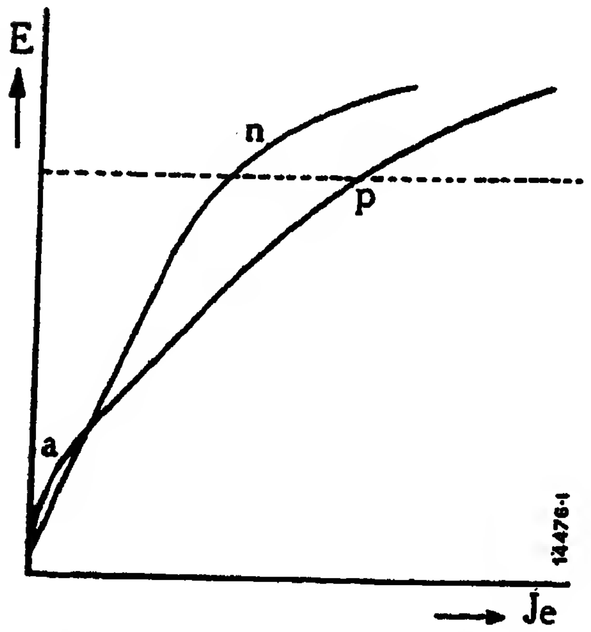


Fig. 72. Pressure curves,
n. Normal excitation machine.
p. Excitation machine provided with regulating poles.

THE EXCITER

Whether the alternator is of the horizontal or vertical type, the usual practice is to provide each machine with an independent built-on exciter, the armature of which is mounted overhung on the rotor shaft. For small units, especially when the speed is low, a built-on exciter is relatively large and costly, and in such cases it is preferable to employ a normal high-speed direct-current generator with belt drive. As a rule, the exciter is a shunt-wound machine with interpoles. The main poles are of the "regulation-pole" type, which enable the alternator voltage to be controlled entirely by a regulator in the shunt circuit of the exciter. In this way, a regulator in the main field circuit can usually be dispensed with and the disadvantages of high first cost and heavy regulating losses avoided.

GENERAL ARRANGEMENT

Horizontal alternators are generally constructed with two bearings supported upon a common bedplate with the stator. In many cases, however, particularly when the stator frame is of large diameter, a common bedplate becomes inconveniently heavy and can well be replaced by separate sole plates for the two bearings and for each foot of the stator (Fig. 69).

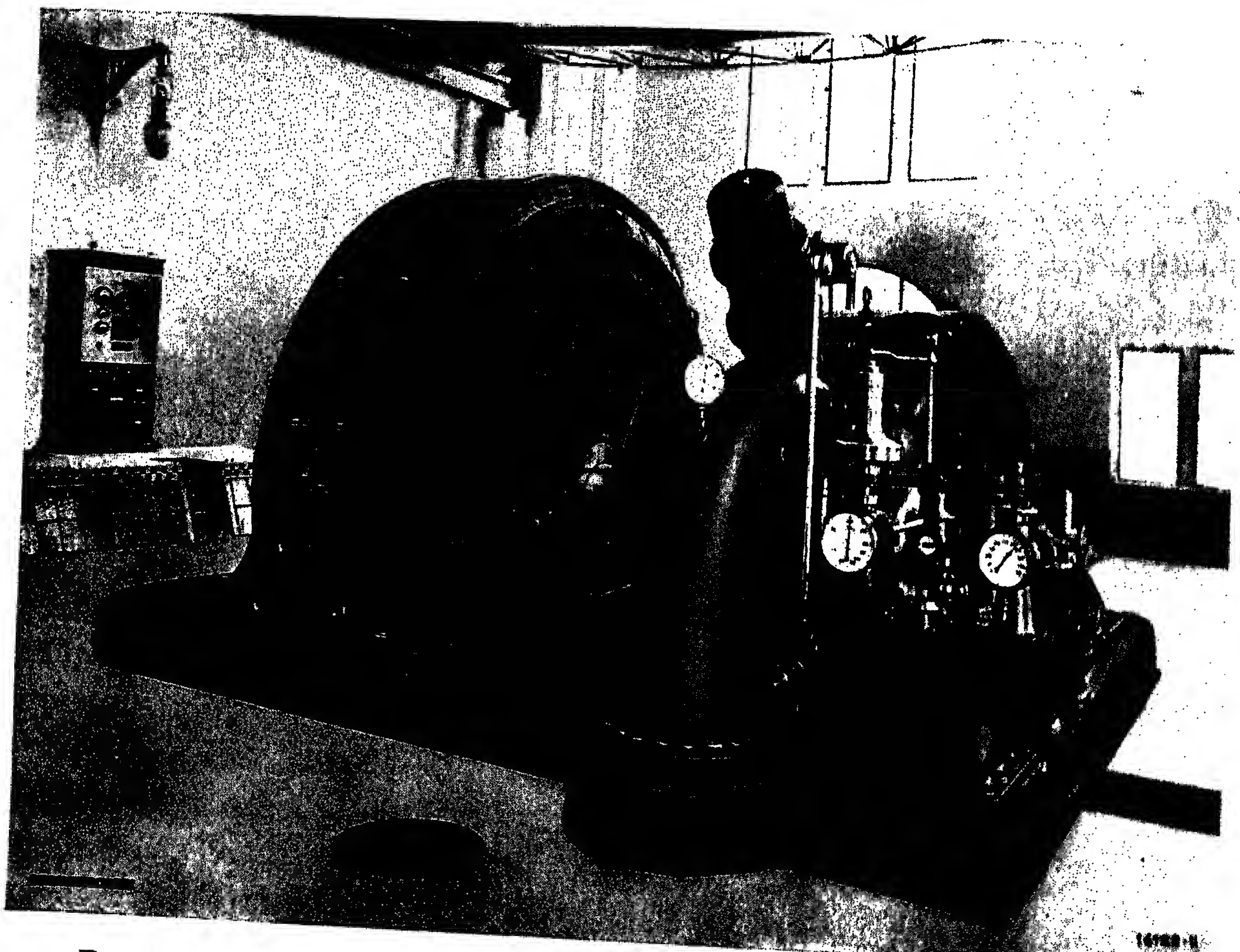


Fig. 73. Three-phase alternator 12,000 kVA, 8000 V, 50 cycles, 300 r. p. m., in the Löntsch Power Station of the North-East Switzerland Power Supply Co.

When the alternator is coupled directly to the turbine a number of different arrangements are possible:

1. The alternator and turbine may each be provided with two bearings, the drive being transmitted either by a flexible coupling (for small powers only), or by a rigid flange coupling (Fig. 70).
2. The alternator and turbine may be built together as a three-

bearing set. In this case, the third bearing is as a rule outside the turbine, but to be considered as part of it; the flange coupling of the shafts is situated on the turbine side of the central bearing, which must be strengthened to take the extra load placed upon it (Fig. 70).

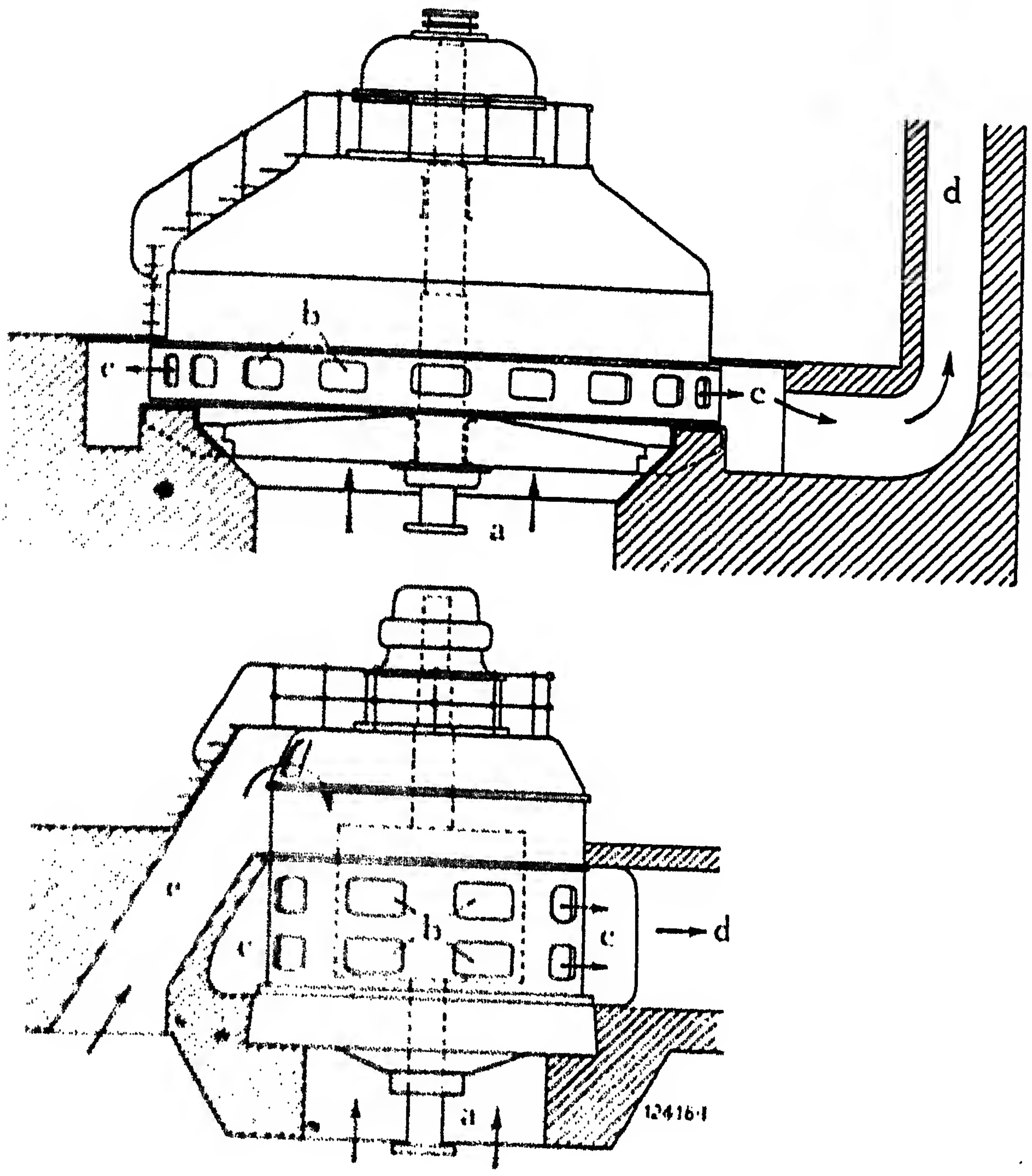


Fig. 74. Ventilation schemes for vertical-shaft alternators.

3. The turbine runner may be arranged overhung on the generator shaft, the whole set having two bearings only. Under these circumstances, the bearing on the turbine side carries a very considerable additional load, and it is therefore necessary for both shaft and bearing to be correspondingly strengthened (Figs. 73, 88 and 91).

The arrangement chosen in any individual case is not only a question of first cost, but depends primarily upon the conditions of space. With four-bearing sets, standard machines can be employed, whereas sets with three or two bearings only, although they enable the axial length to be reduced, involve alterations in the design of bearings, shafts, and baseplates, which naturally increase both the price of the machines and the time of delivery. Consequently the two or three-bearing arrangement is as a rule only considered when the alternator is large.

Vertical-shaft alternators are usually provided with two guide bearings, carried by radial brackets, one above and one below the rotor. The upper bracket supports the thrust bearing also and is correspondingly heavily constructed.

In certain cases the lower guide bearing of the alternator can be dispensed with, if the turbine bearing is situated sufficiently high.

The arrangement of the cooling-air channels in the foundation depends to a very great extent upon the particular conditions under which the machine is installed, but the arrangements illustrated in Figs. 16 and 74 for horizontal and vertical-shaft machines respectively may be regarded as typical.

AIR-FILTERS AND COOLING

Filters for cleaning the cooling-air are as a rule unnecessary in hydro-electric plants, except when the power station is situated in the immediate neighbourhood of works where the manufacture of cement, carbide, or some similar material is carried out. In the same way, a closed-circuit cooling system with an air cooler is only necessary in exceptional cases. By suitably designing the air intake and channels, it is possible to arrange for a supply of sufficiently pure air without the necessity for any special equipment such as would increase the cost of the plant very appreciably. It is advisable to provide both the intake and discharge channels for the cooling air with shuters or valves which can be closed in the event of an outbreak of fire, so that the volume of air having access to the interior of the machine is limited, and the damage minimised.

Large Brown Boveri alternators have recently been fitted with a Siebenmann fire-extinguishing equipment. This consists of shutters capable of closing the air intake and discharge passages completely, as near as possible to the machines, combined with a supply of liquid carbon dioxide contained in steel cylinders situated in the generator pit. Should the windings catch fire, a single lever is actuated which closes the air shutters and opens the valves of the gas cylinders automatically. A definite mixture of carbon dioxide and air is immediately formed and circulated

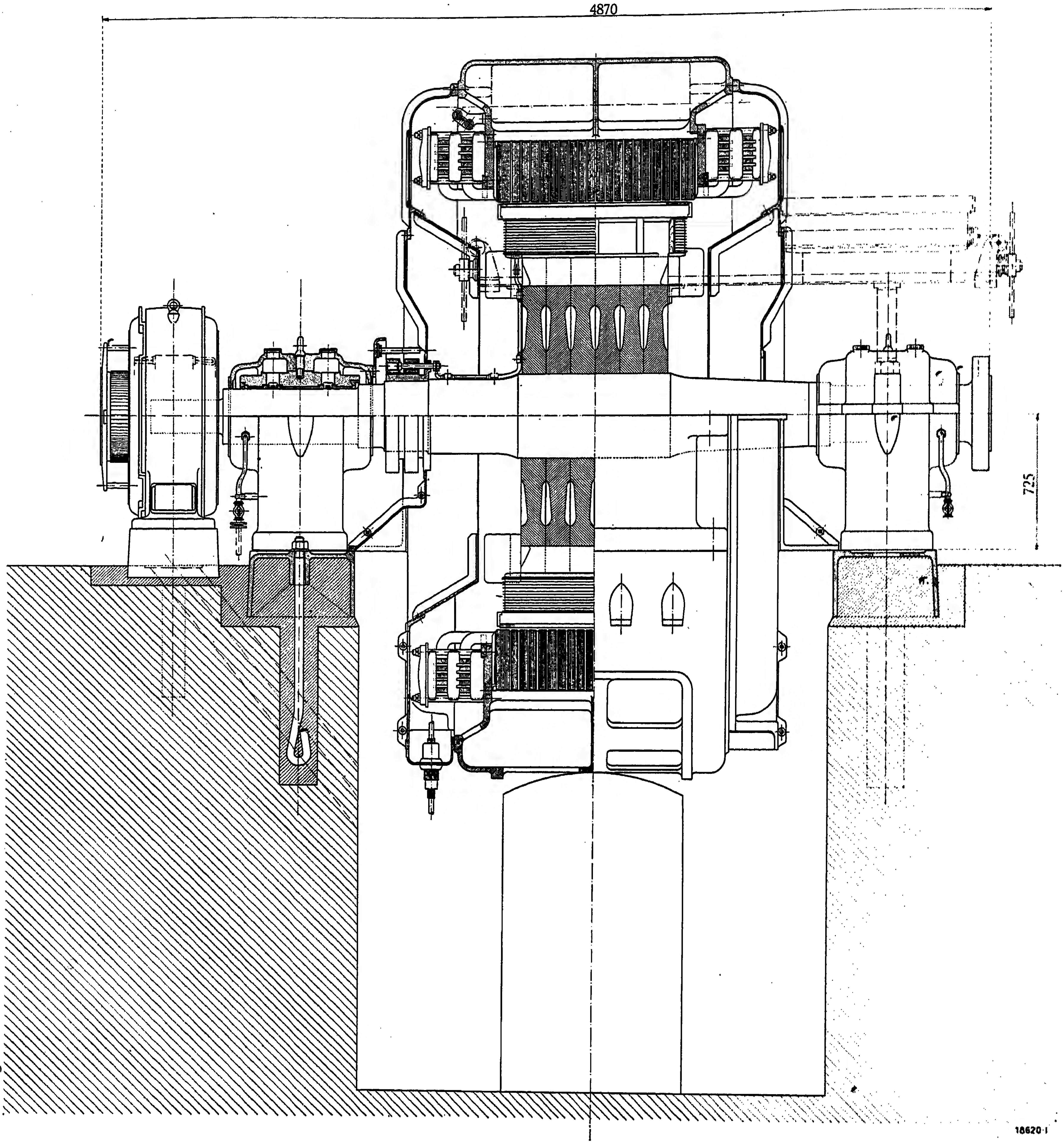


Fig. 75. Section through a three-phase alternator 7000 kVA, 9500/10,500 V, 42/46 cycles, 504/552 r. p. m.
Four such generators are installed in the Matese Power Station of the Società Meridionale di Elettricità in Naples.

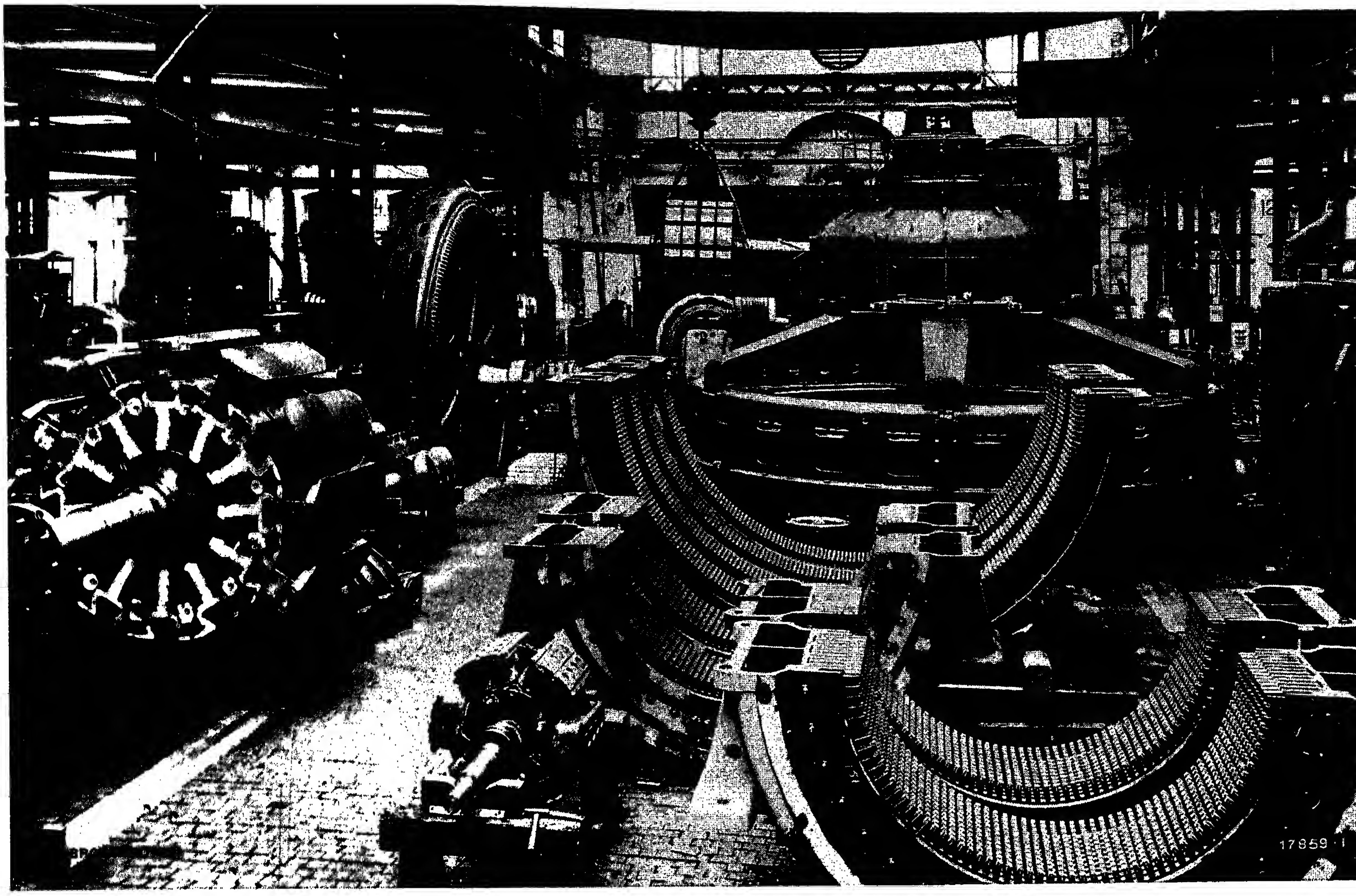


Fig. 76. View of erection shop for hydro-electric alternators.

throughout the machine by the revolving rotor, so that the flames are completely extinguished within a few seconds. In this way, it is possible to combat effectively fires which would otherwise have very destructive results.

DISMOUNTING

It is important, particularly with large machines, that parts subject to wear should be as easily and rapidly accessible as possible. The manner in which this object is achieved in Brown Boveri alternators is amply indicated in the description of the various component parts and the accompanying illustrations. Brief reference should be made, however, to the method of dismantling the stator winding or parts of it; in most cases, this operation must be preceded by dismantling the rotor or individual poles. With vertical-shaft machines, after the upper bearing bracket has been removed, the rotor can be lifted away from the stator by means of the crane, or, if the method of attachment allows it, single poles can be removed from the rotor either upwards or downwards, the bearing bracket remaining in position.

The stator of horizontal-shaft machines with a small number of poles (4—8) is either constructed in one piece or must be treated as such once it has been wound. In these cases the rotor has to be placed in position and removed axially, for which purpose it is usually necessary to remove both the bearings, or else the crane must be sufficiently powerful to lift the stator and rotor together. With larger machines, in which the poles are dovetailed into the pole wheel, a pole-removing device is supplied, enabling the poles to be withdrawn singly (see Fig. 75); individual stator coils can then be removed or put into position in the resulting space; e. g., the

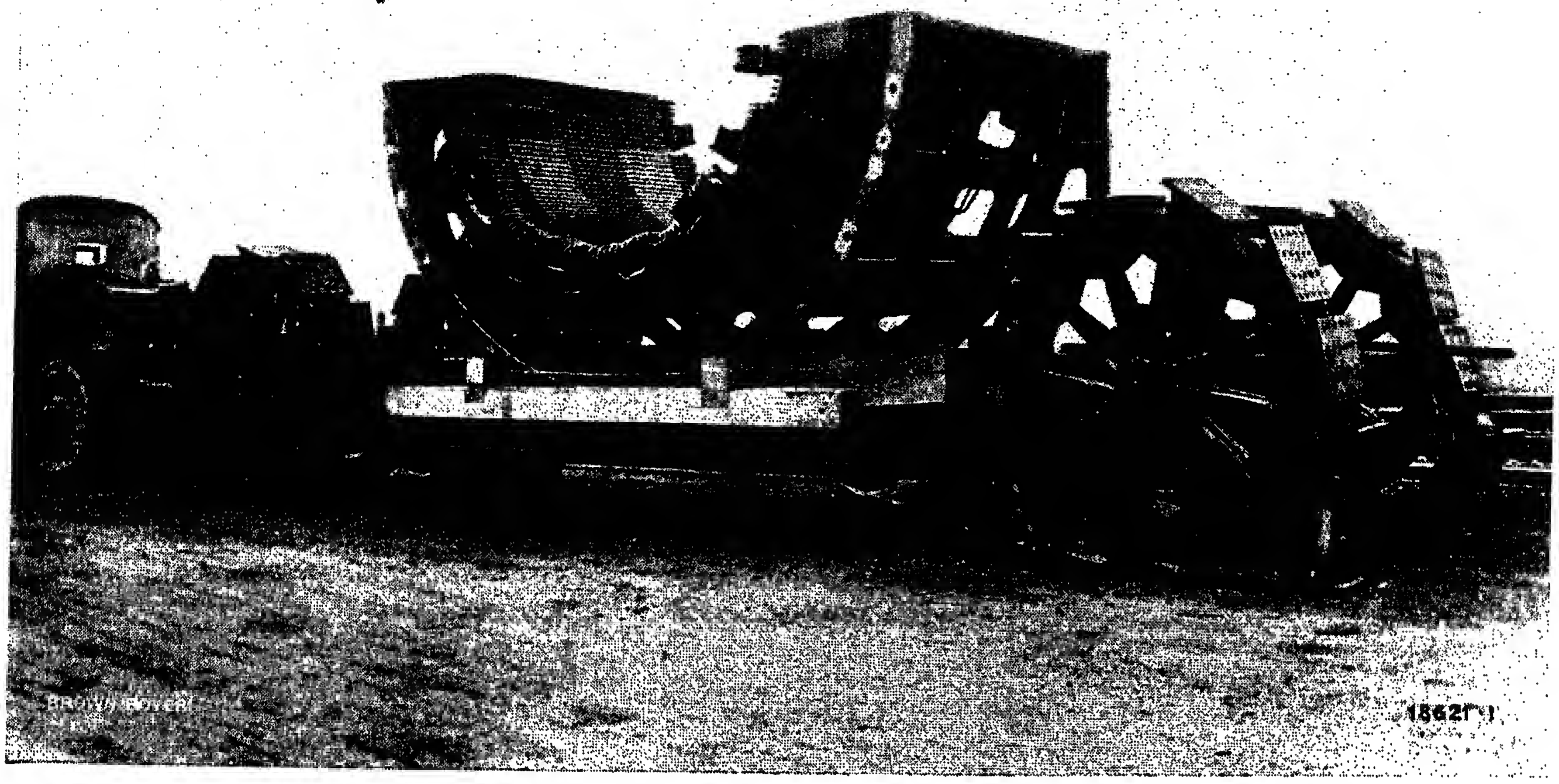


Fig. 77. Transporting a half of the stator for a vertical-shaft alternator, 16,500 kVA, 500 r. p. m.

coils at the points of division of the two parts of the stator can be removed to enable the upper half of the stator to be lifted.

When the stator windings are in half-closed slots, it is unnecessary to dismantle the rotor at all, as the individual stator bars can be withdrawn axially after their ends have been disconnected. When the space in the alternator pit is insufficient for this purpose, the stator and rotor must be dismantled unless the stator can be rotated about the axis. In spite of the higher first cost involved, this latter solution is emphatically to be recommended for large units.

GEARED DRIVES

Under certain conditions, such as when the speed of the turbines is low and direct-coupled generators would be too costly or too large, it may be an advantage to employ a geared drive. Fig. 79 shows a plant in which vertical turbines drive standard three-phase alternators through bevel gearing. Fig. 80 shows an installation in which three vertical turbines are geared through bevel wheels on to a common shaft coupled to a generator. While the application of bevel wheels is very limited with regard to the power transmitted and the gear ratio, modern spur gearing is suitable for very high powers and large ratio. By this means, for example, it is possible to drive a high-speed generator at 750—1000 r. p. m. by a turbine running at 100 r. p. m., in which case the generator is naturally very much cheaper and has a somewhat higher efficiency than if it were direct coupled. As the cost of the gearing is considerable, it must be

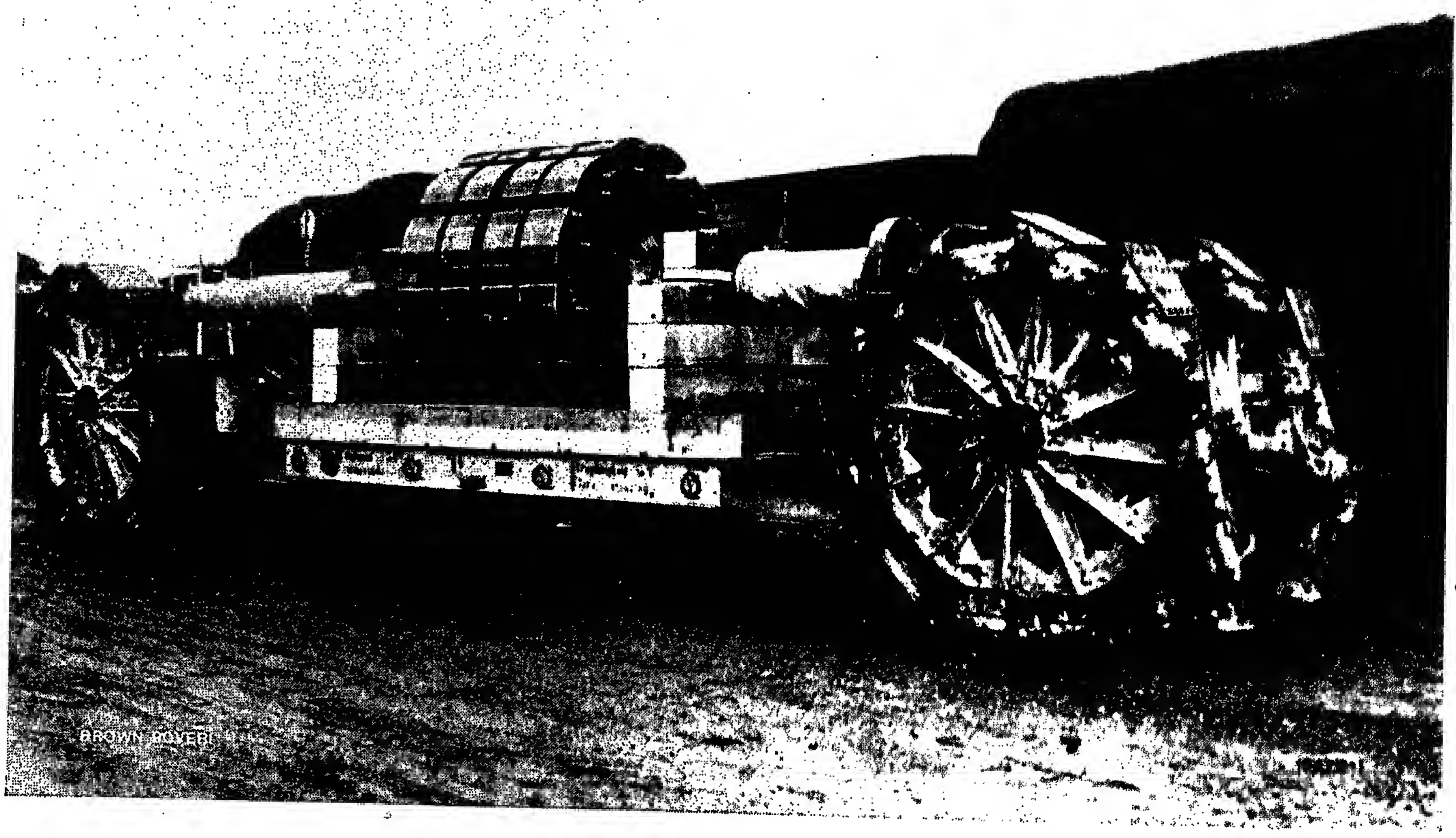


Fig. 78. Transporting a rotor spider for a vertical-shaft alternator 16,500 kVA, 500 r. p. m.

carefully investigated in every case whether geared drive or direct coupling is the more advantageous. It is generally found that the boundry conditions beyond which gearing should be employed are an output of 1000 to 2000 kW and a turbine speed of 80—100 r. p. m. Fig. 81 shows a plant in which a high-speed alternator is driven through gearing of this kind.

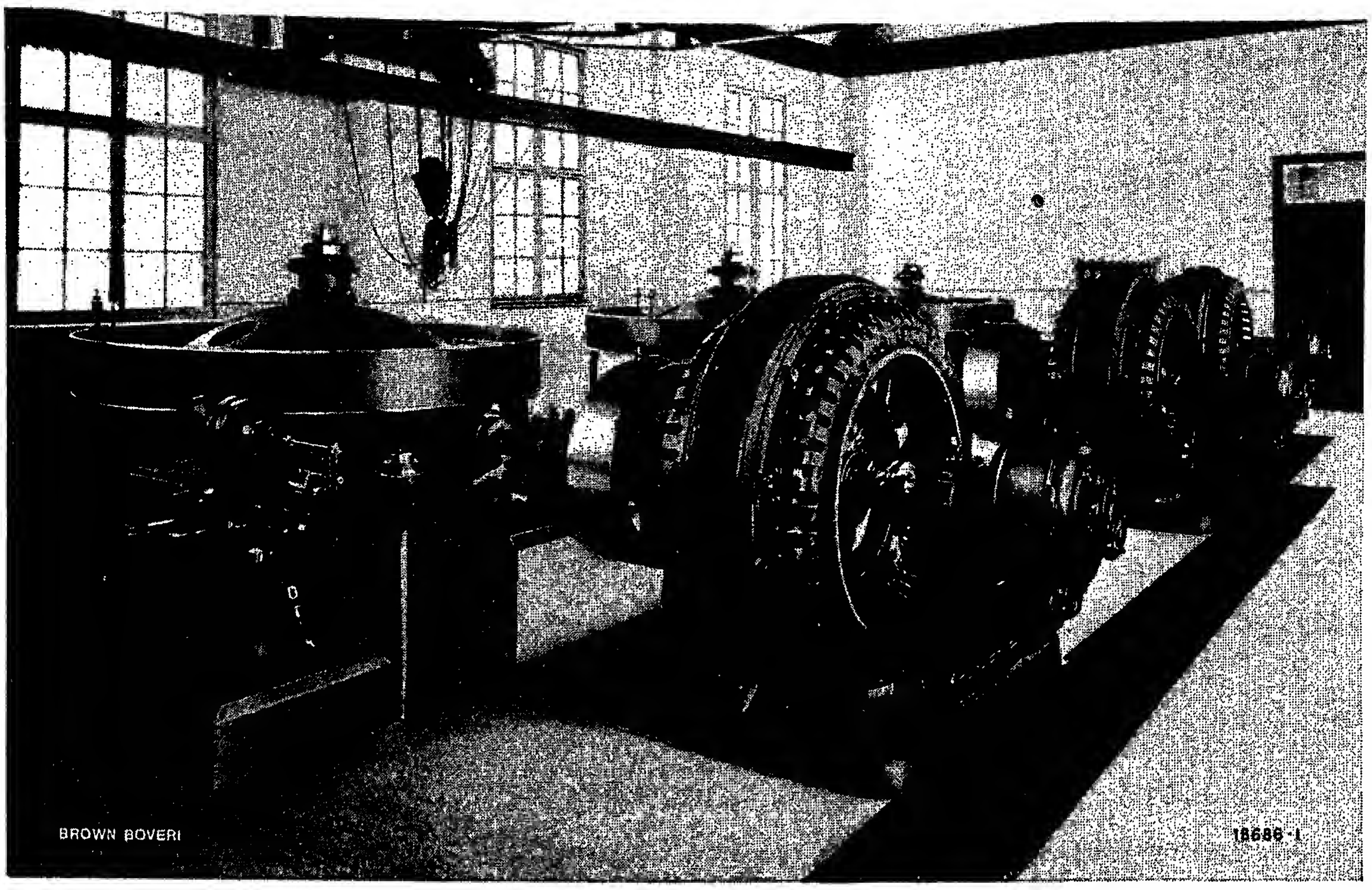


Fig. 79. Bevel gearing in Siglingen Power Station. Two three-phase alternators each 270 kVA, 5250 V, 50 cycles, 500 r. p. m. and one single-phase alternator, 180 kVA, 5250 V, 50 cycles, 500 r. p. m., are shown.

For many years, Brown, Boveri & Co. have successfully manufactured gearing, particularly for marine drives, for outputs up to about 12,000 H.P., with the result that they have accumulated much valuable experience in this branch. That this is generally recognised is indicated by the fact that Brown Boveri gearing has been ordered for hydro-electric plants, the turbines and alternators of which were supplied by other firms.

INDUCTION GENERATORS

Up to this point, reference has been made to synchronous generators only; for the sake of completeness, however, the induction generator should also be briefly mentioned. Machines of this type are occasionally employed in small power stations, working in parallel with a larger station containing synchronous generators. In such cases, the induction generator has the advantages of greater simplicity — simplified switchgear and no turbine governor — and simpler attendance — no paralleling and no exciter. On the other hand, it has the disadvantage that it takes wattless current from the mains, this constituting an additional load on the

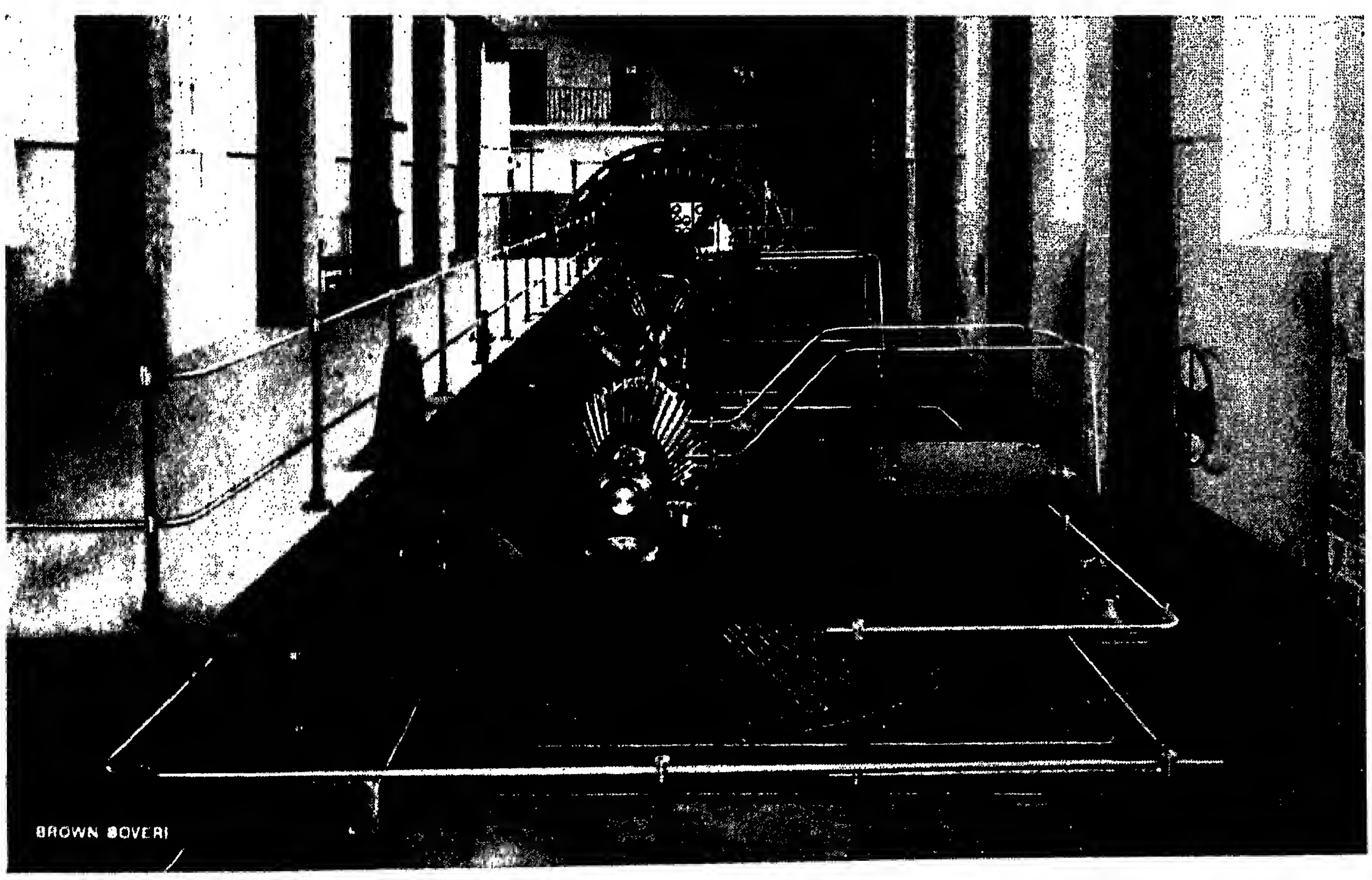


Fig. 80. Bevel gearing for a three-phase alternator, 1600 kVA, 3150 V, 50 cycles, 125 r. p. m., in the Mainaschaff Power Station of the Electrical Power Supply Co.

distribution system and the synchronous machines in the central station. An induction generator can consequently only furnish power in conjunction with one or more synchronous alternators; i. e., it is incapable of working alone.

Induction generators will probably be somewhat less frequently employed in future since Brown, Boveri & Co. have shown that the automatic synchroniser makes it possible to build completely automatic power stations which operate in a satisfactory manner when equipped with synchronous machines.

The illustrations in the following pages show some of the large number of installations which have been equipped by Messrs Brown, Boveri & Co., during the last few years.

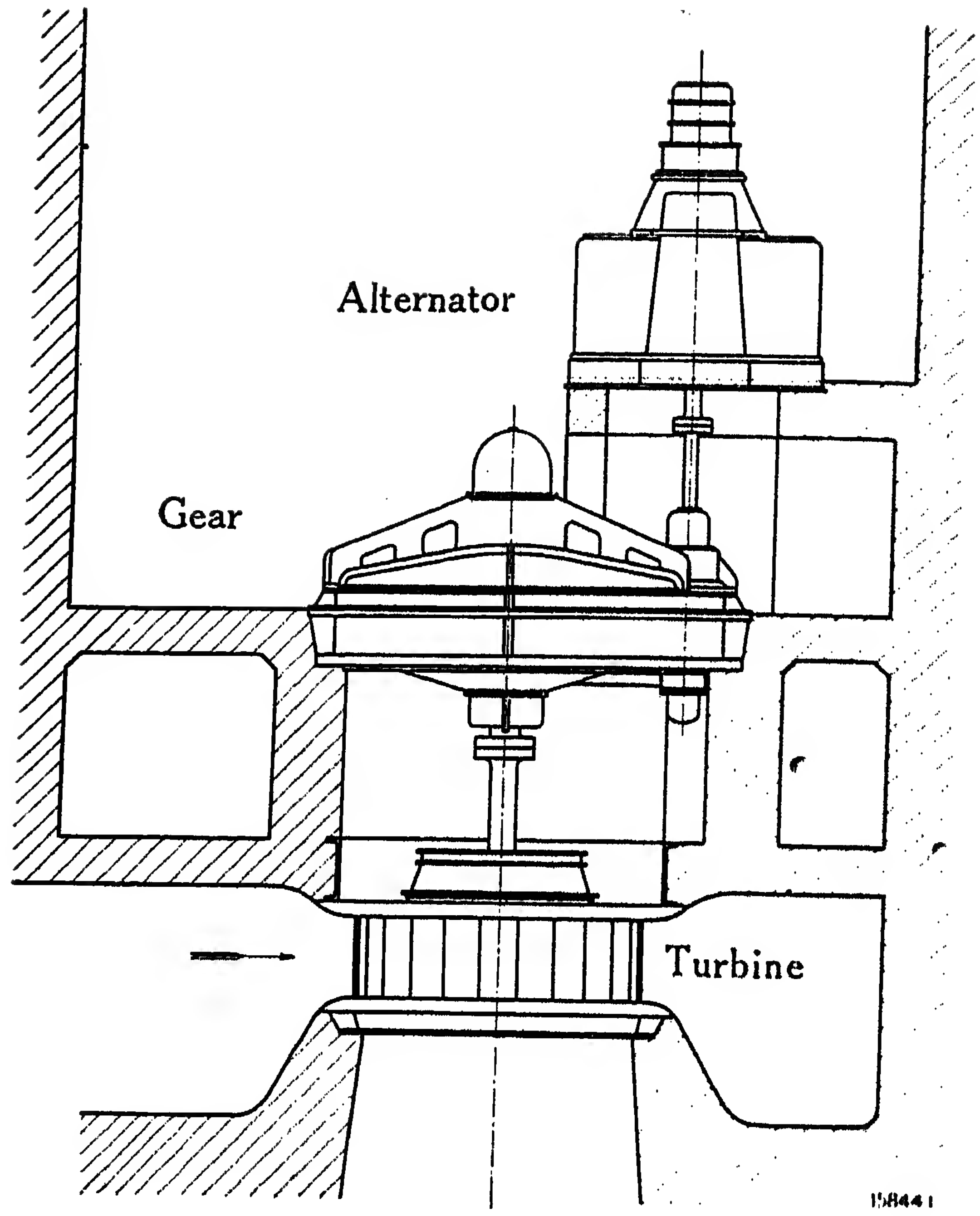


Fig. 81. A three-phase alternator, 2600 kVA, 5000 V, 50 cycles, 750 r. p. m., gear driven; turbine speed 94 r. p. m., in Wieblingen Power Station of the Neckar Co.

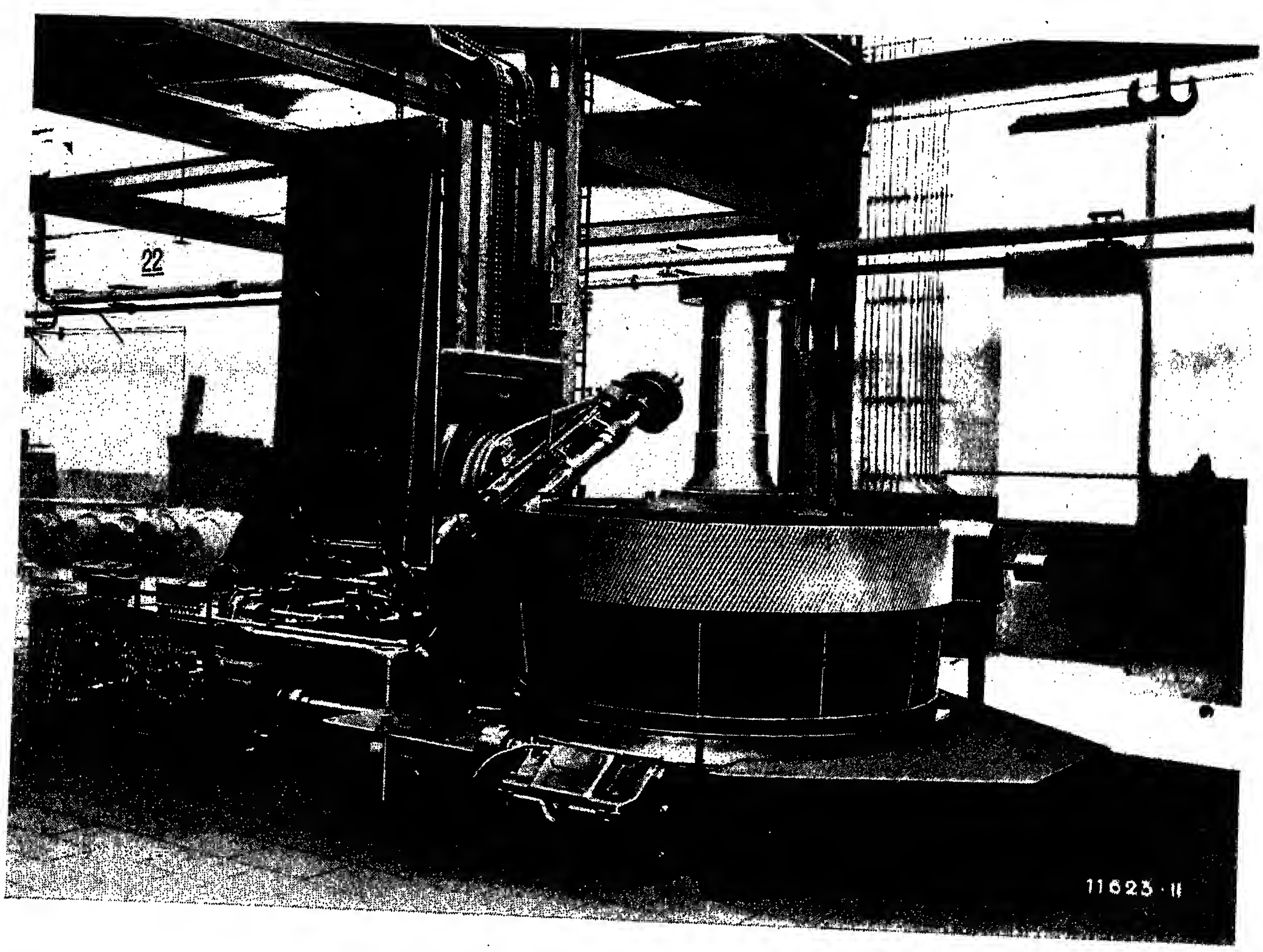


Fig. 82. One of the hobbing machines.

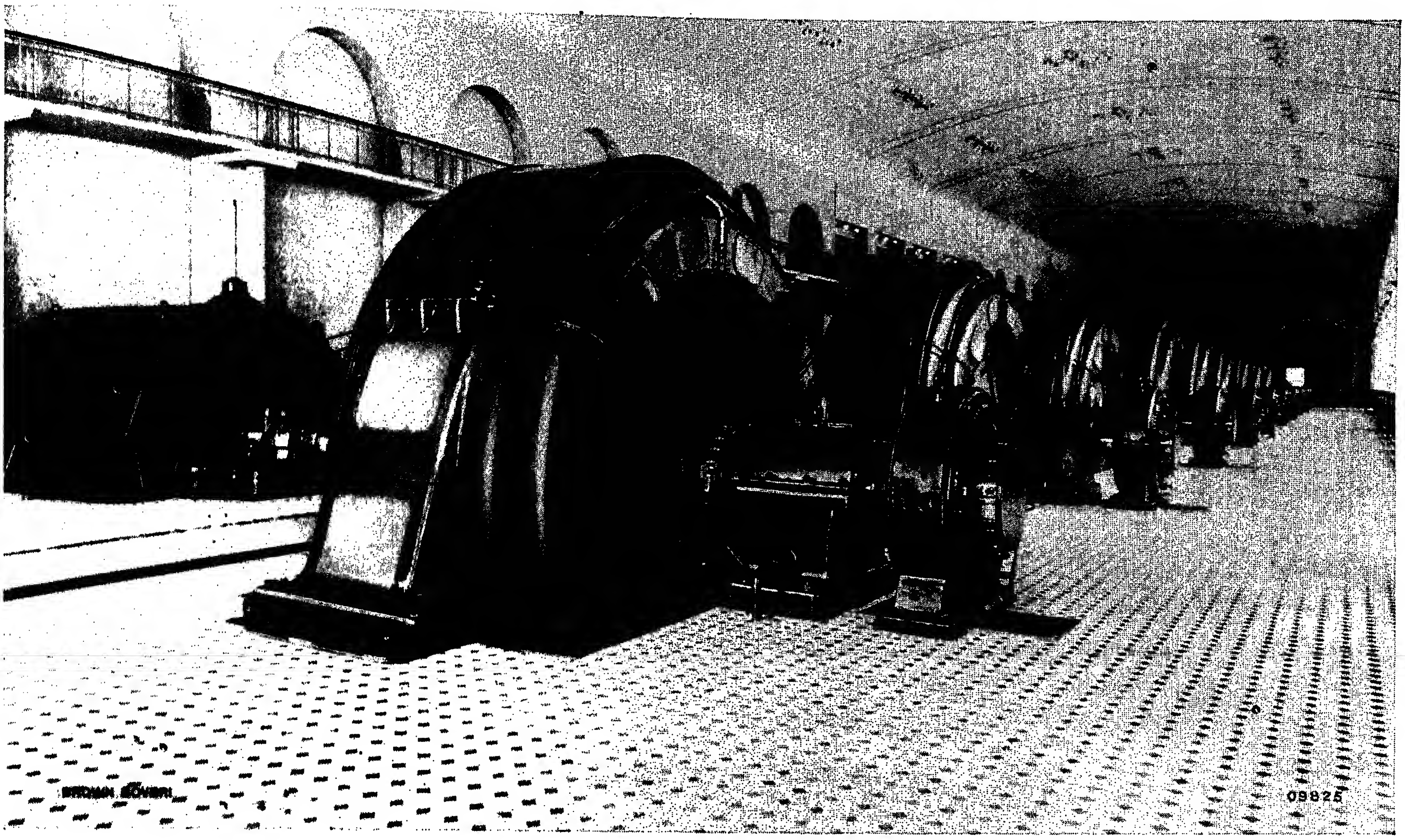


Fig. 83. The machine hall of the Saaheim Central Station at Ryukanfoss (Norway), showing Brown Boveri three-phase alternators each 19,000 kVA, 11,000 V, 50 cycles, 250 r. p. m.

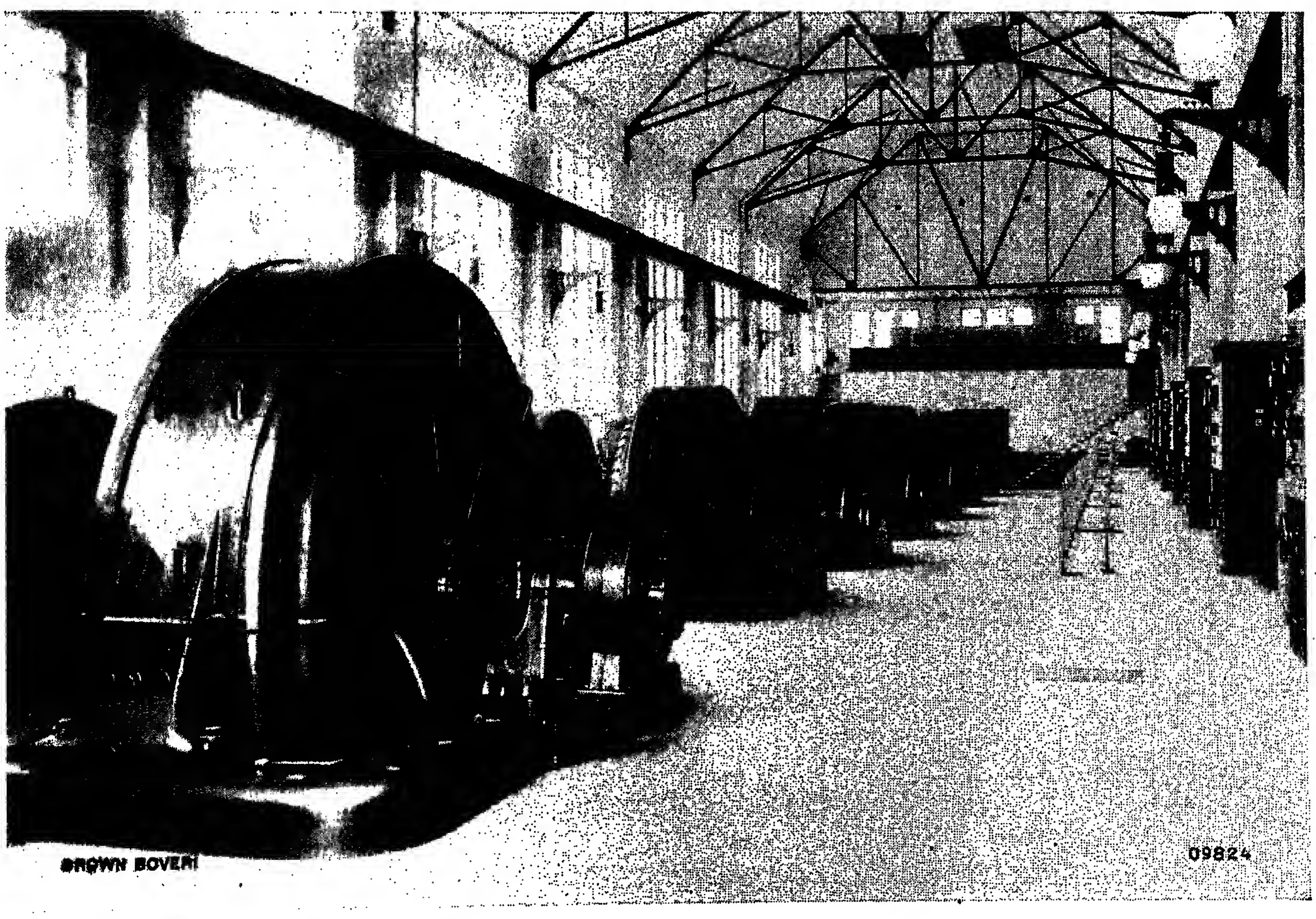


Fig. 84. The machine hall of the Löntsch-Power Station of the North-East Switzerland Power Supply Co.
One, three-phase alternator, 12,000 kVA, 8000 V, 50 cycles, 300 r. p. m. and six, three-phase alternators each 6000 kVA, 8000 V, 50 cycles, 375 r. p. m. are installed. The machine shown in Fig. 73 is erected in a special building.

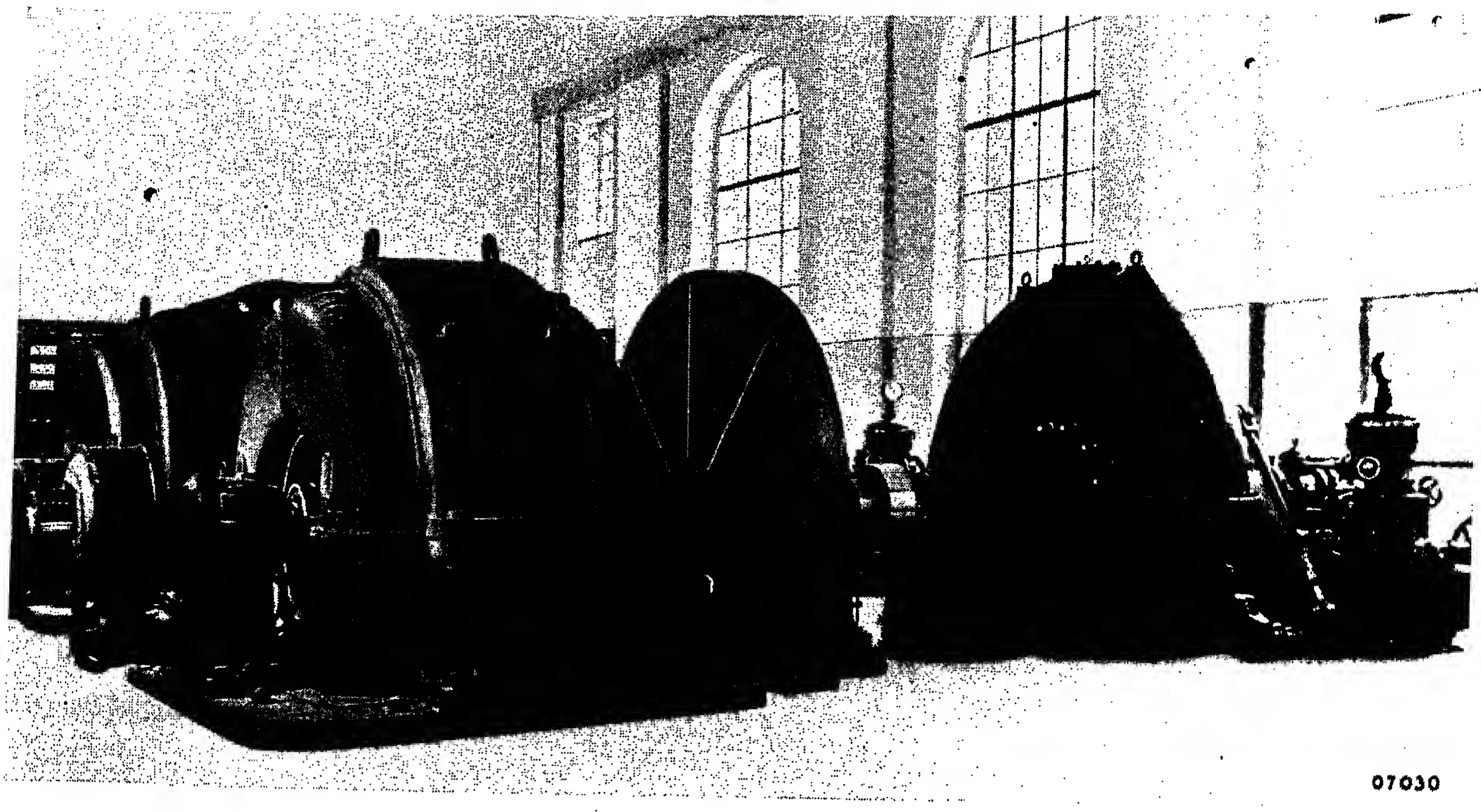


Fig. 85. The Massaboden Power Station of the Swiss Federal Railways.
Two three-phase alternators each 2700 kVA, 3300 V $16^2/_3$ cycles, 500 r. p. m.

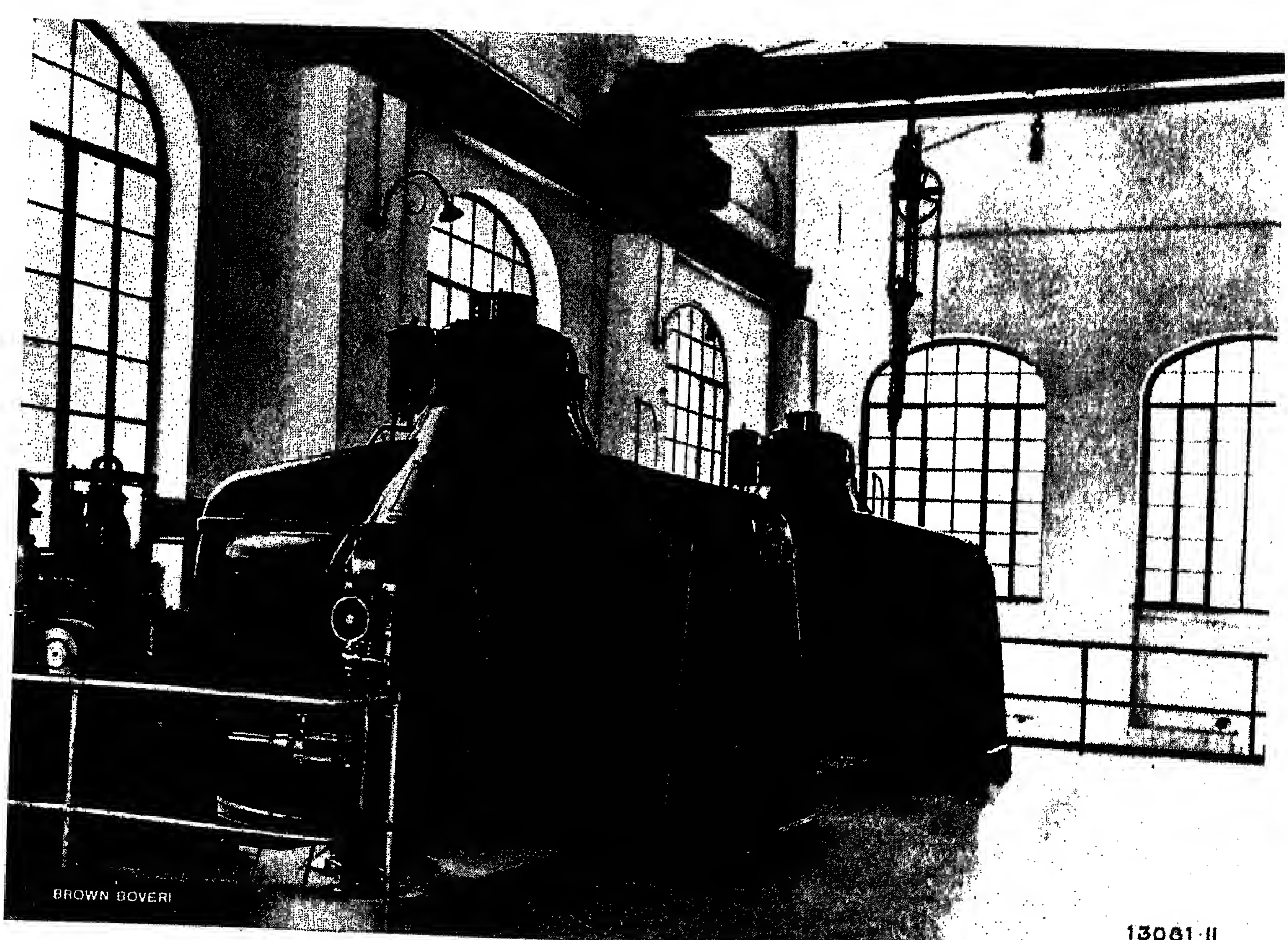


Fig. 86. Two of the three three-phase alternators each 3000 kVA, 5000 V, 50 cycles, 750 r. p. m.,
installed in the Buitreras Power Station of the Soc. Hidro Electrica del Guadiaro (Spain).

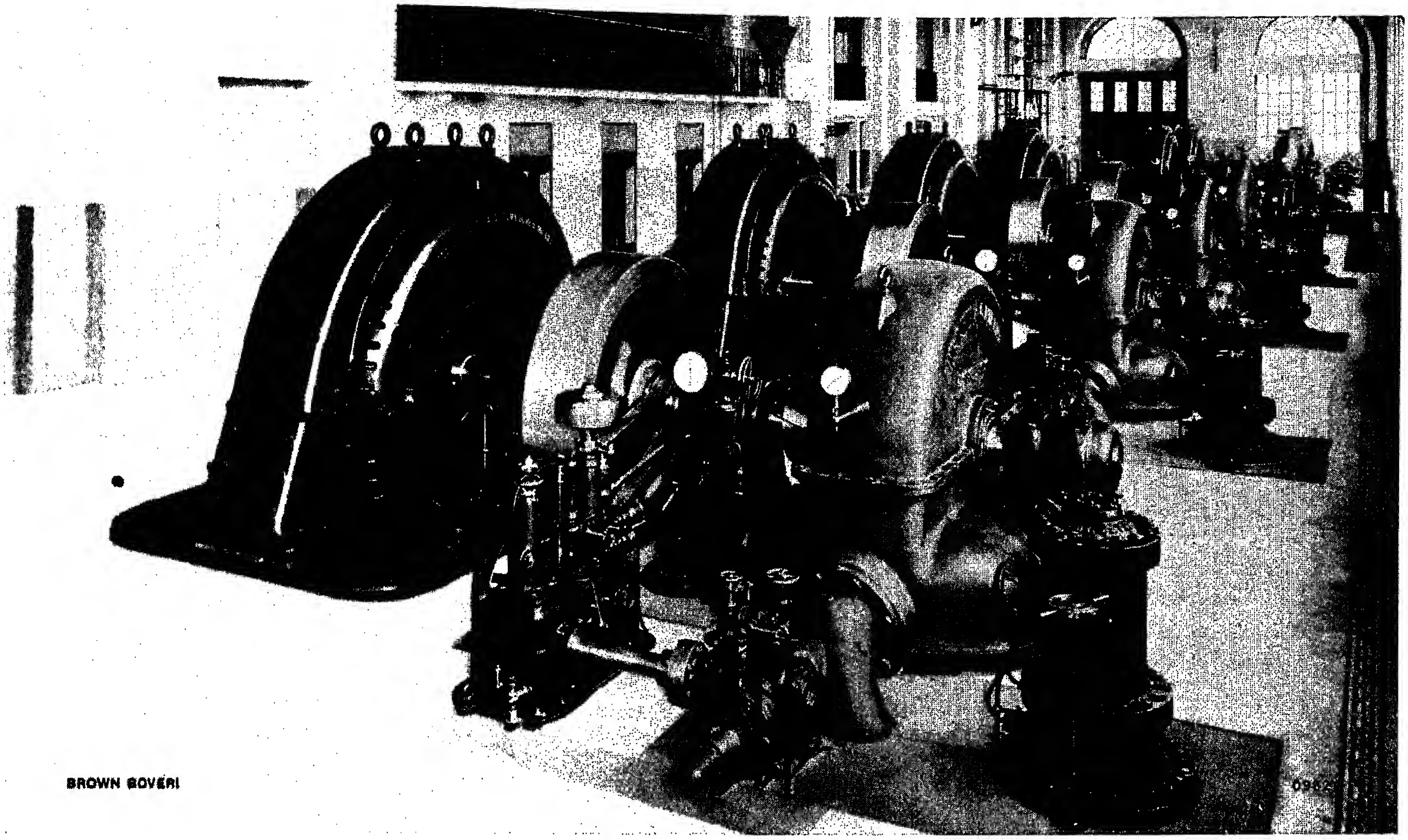


Fig. 87. The Varzo Power Station.
Four three-phase alternators each 3400 kVA, 3300 V, 42 cycles, 504 r. p. m. are installed.

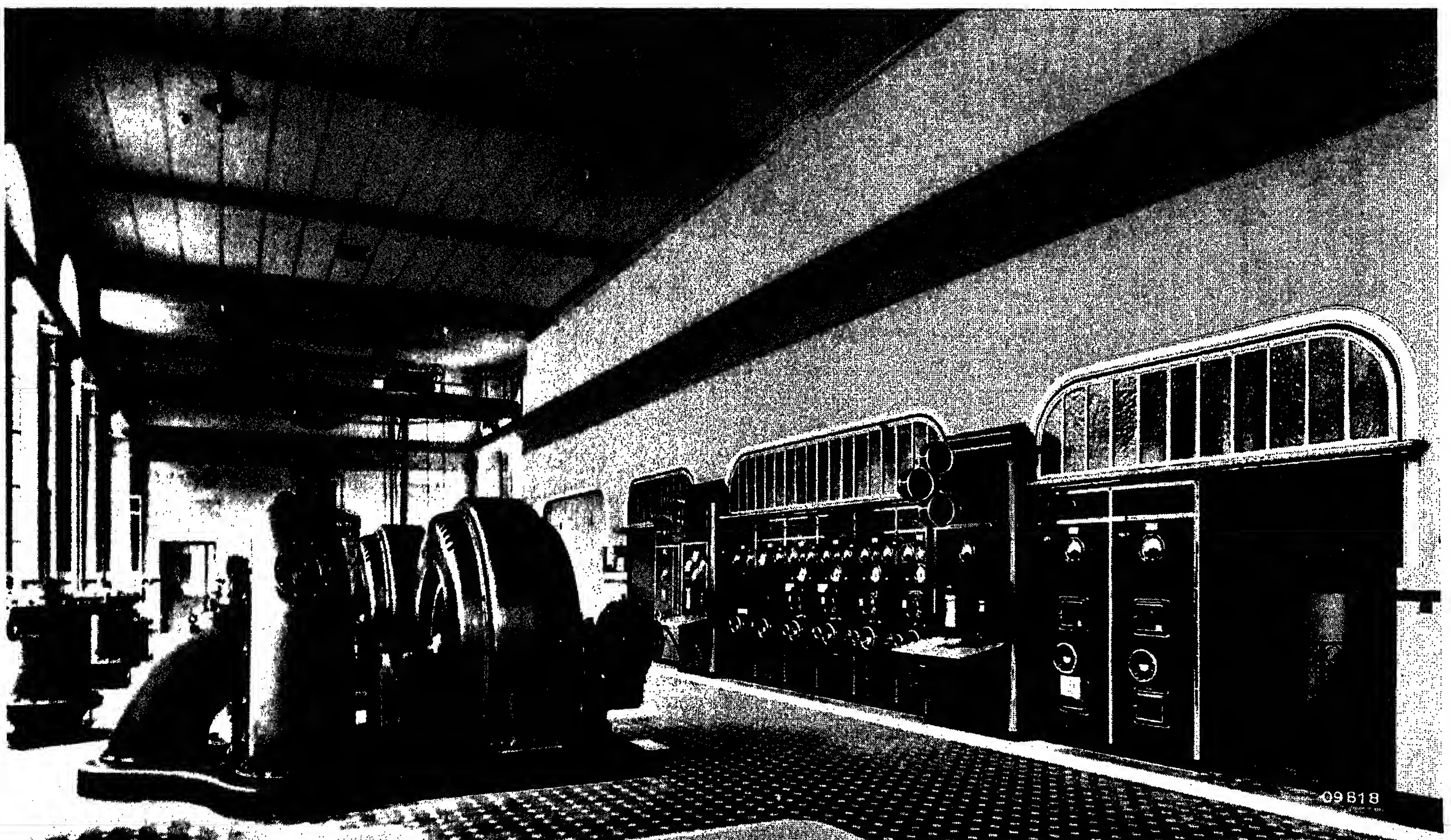


Fig. 88. Three of the four, three-phase alternators in Boudry Power Station, each 1200 kVA, 4000 V, 50 cycles, 750 r. p. m.

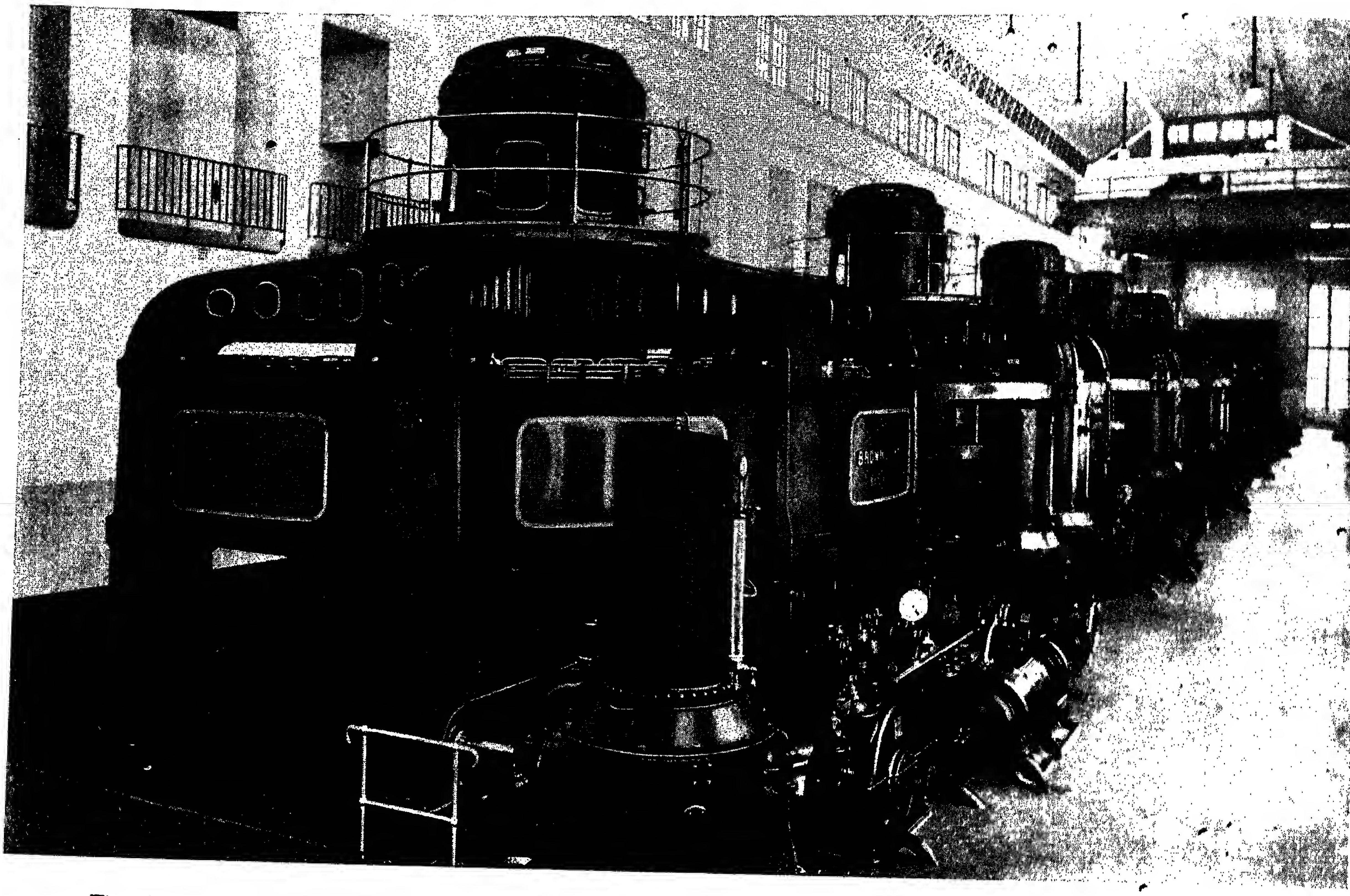


Fig. 89. The Gösgen Power Station of the Olten-Aarburg Electrical Power Supply Co., showing six of the seven, three-phase alternators, each 7050 kVA, 8400 V, 50 cycles, 83·3 r. p. m.

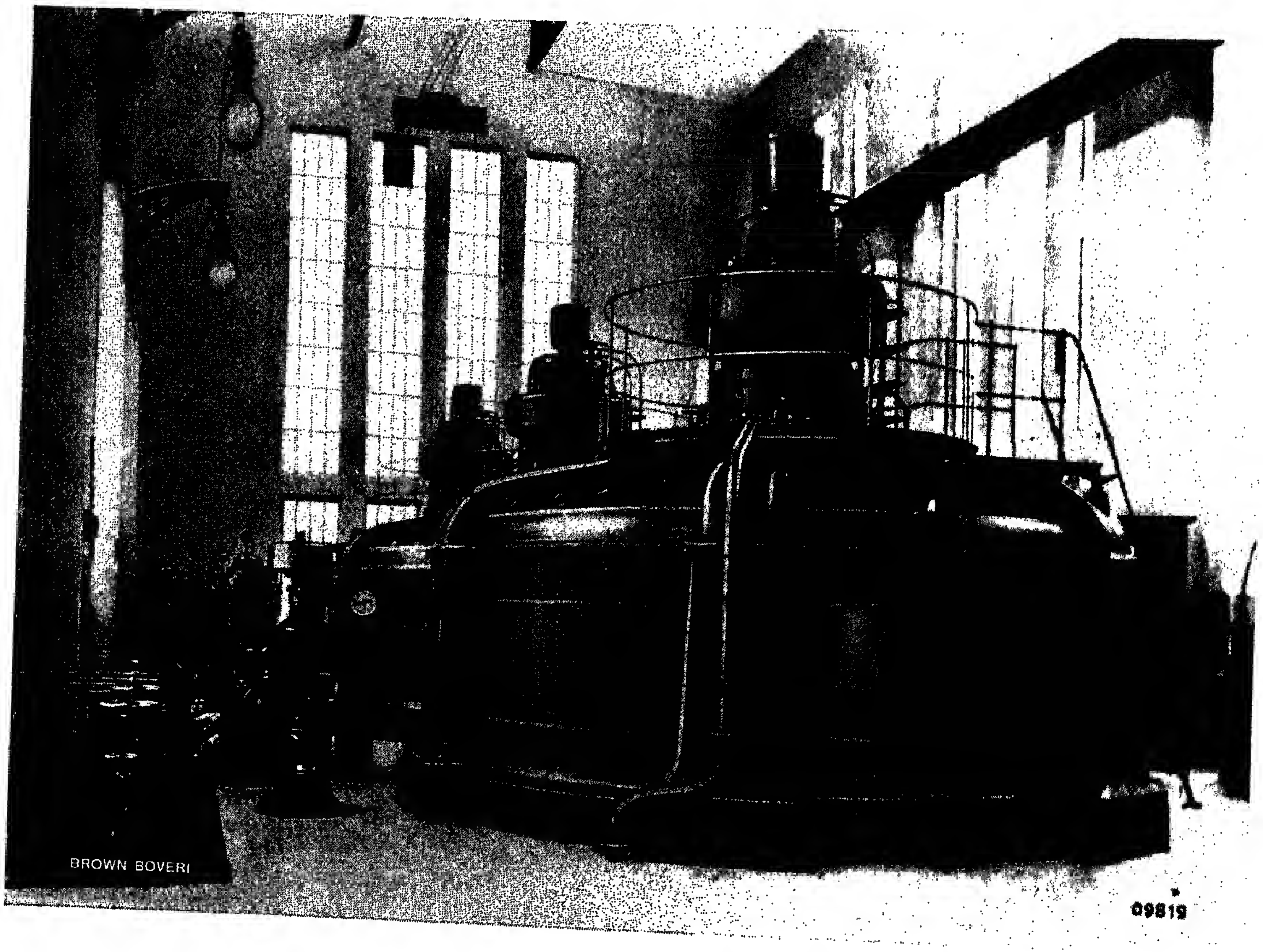


Fig. 90. The Biaschina Power Station, containing three, three-phase alternators each 8800 kVA, 8000 V, 50 cycles, 300 r. p. m. and one machine for 14,500 kVA, 50 cycles, 300 r. p. m.; only the three-phase machines are shown.

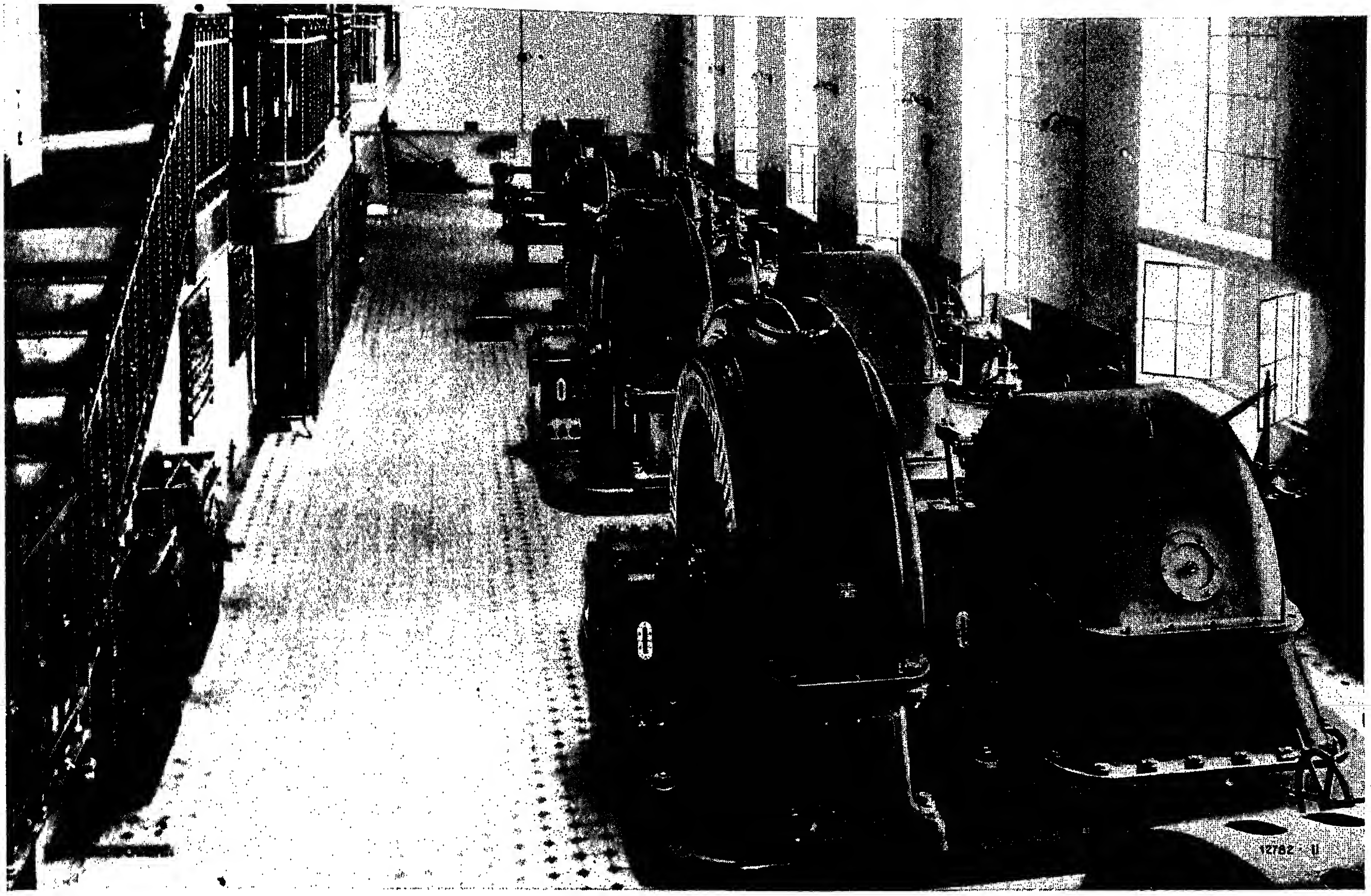


Fig. 91. The Gordola Power Station on the Verzasca.
Two three-phase alternators each 3000 kVA, 4200 V, 50 cycles, 500 r. p. m. and three three-phase alternators, each 920 kVA, 4200 V, 50 cycles, 500 r. p. m. are installed.

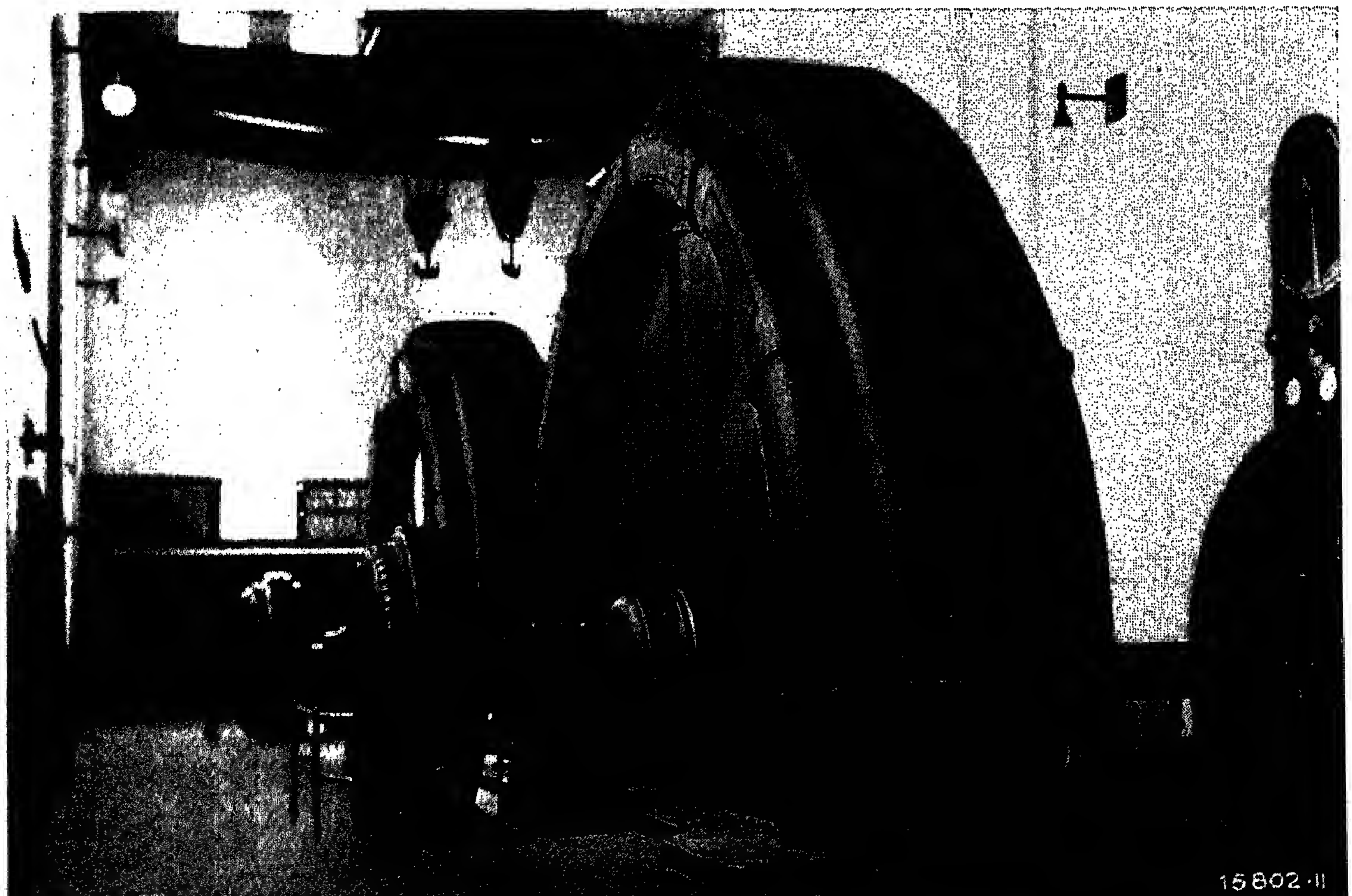


Fig. 92. Two of the four three-phase alternators each 12,000 kVA, 7500 V, 50 cycles, 107 r. p. m.,
installed in the Raanaasfoss Power Station of the Akershus Amts Power Supply Co., Norway.

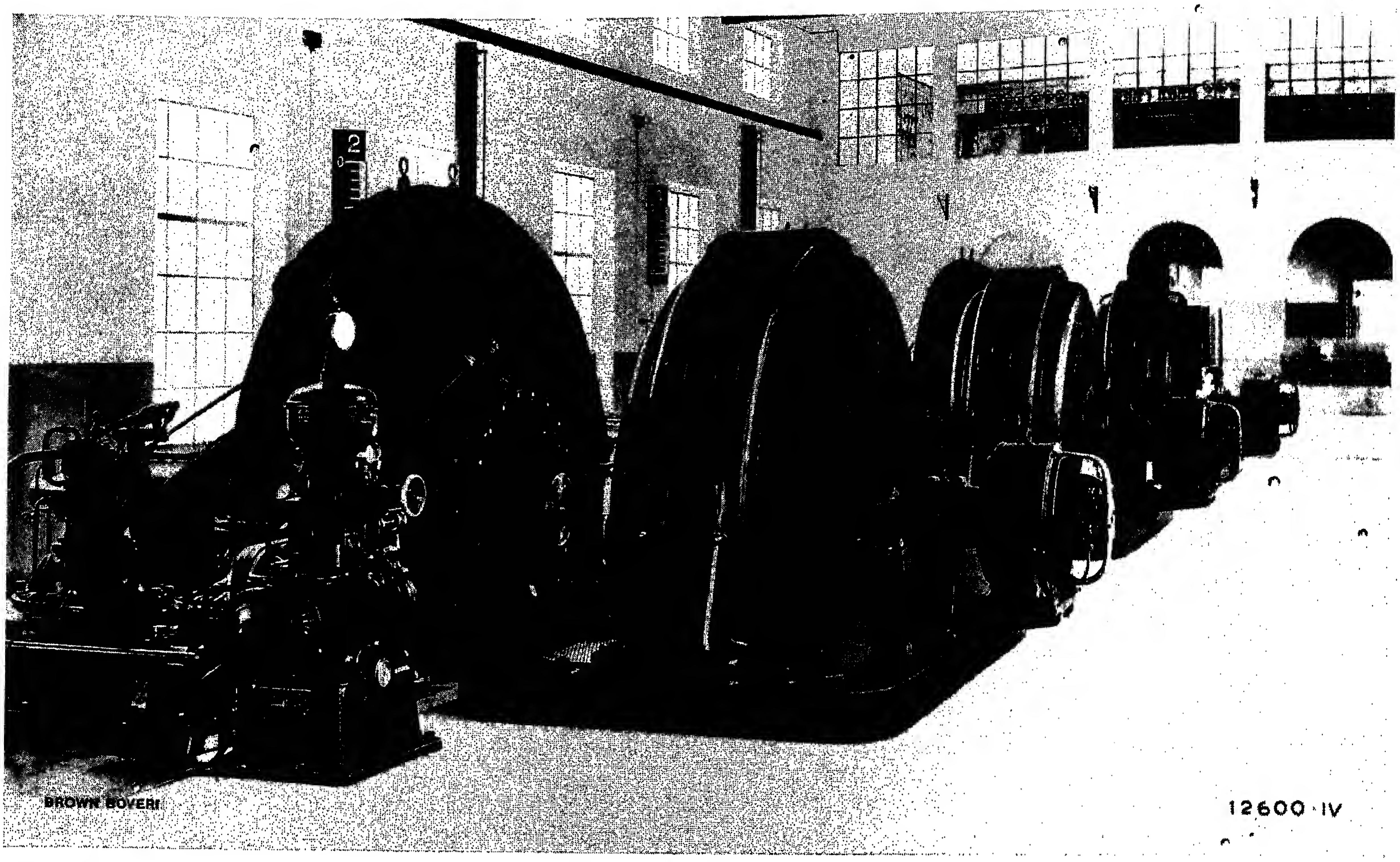


Fig. 93. Three three-phase alternators each 2800 kVA, 6500 V, 50 cycles, 375 r. p. m., in the Bois Noir Power Station at St. Maurice.

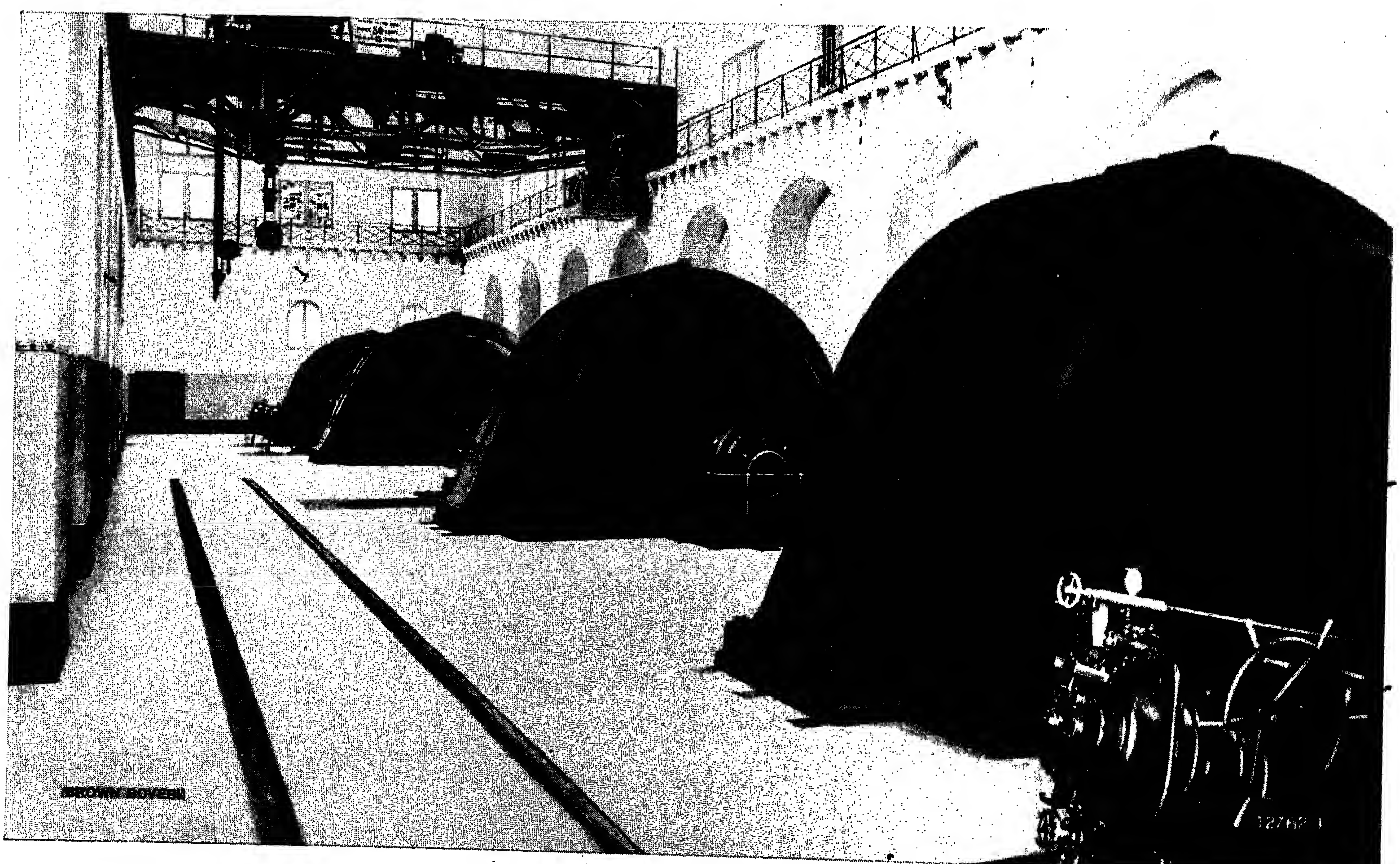


Fig. 94. Four single-phase alternators each 9000—11,500 kVA, 15,000 V, $16^{2}/_{3}$ cycles, 333 r. p. m., installed in the Ritom Power Station of the Swiss Federal Railways.

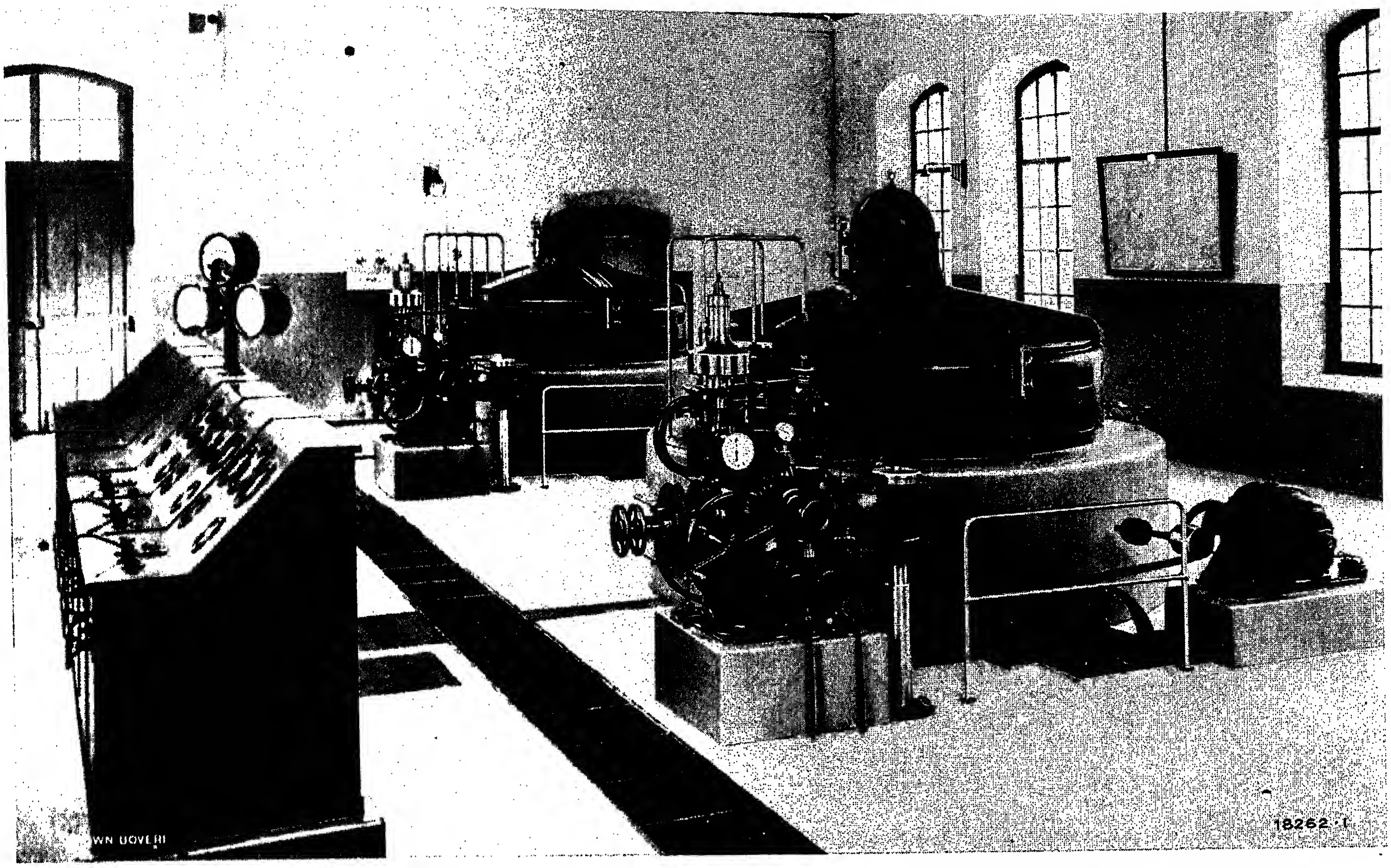


Fig. 95. Three-phase alternators, each 250 kVA, 3800 V, 40 cycles, 172 r. p. m. in the Matte Power Station of the Electricity Supply Co., Berne.

Three similar alternators are installed in this station; on left the switchdesk is shown.

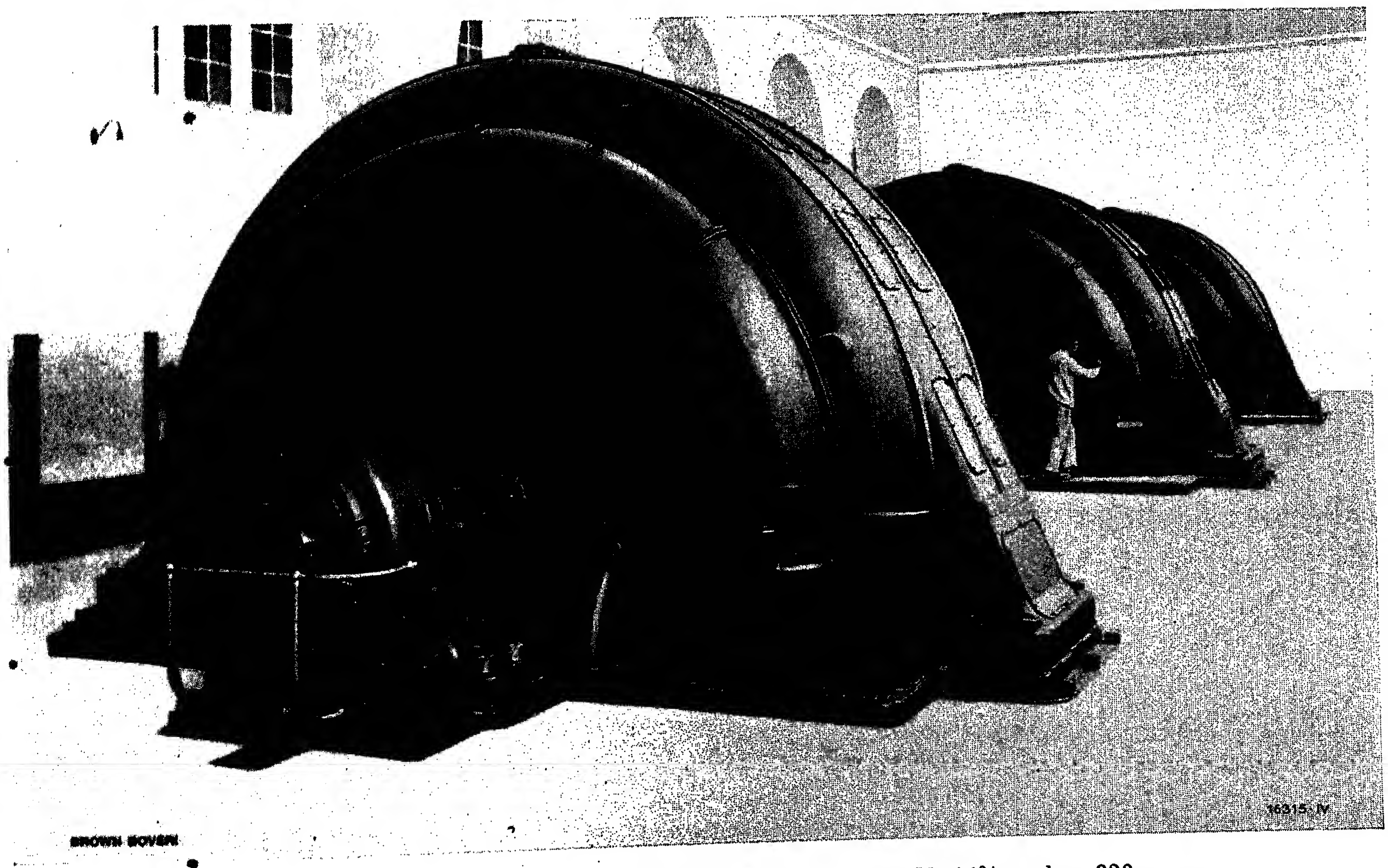
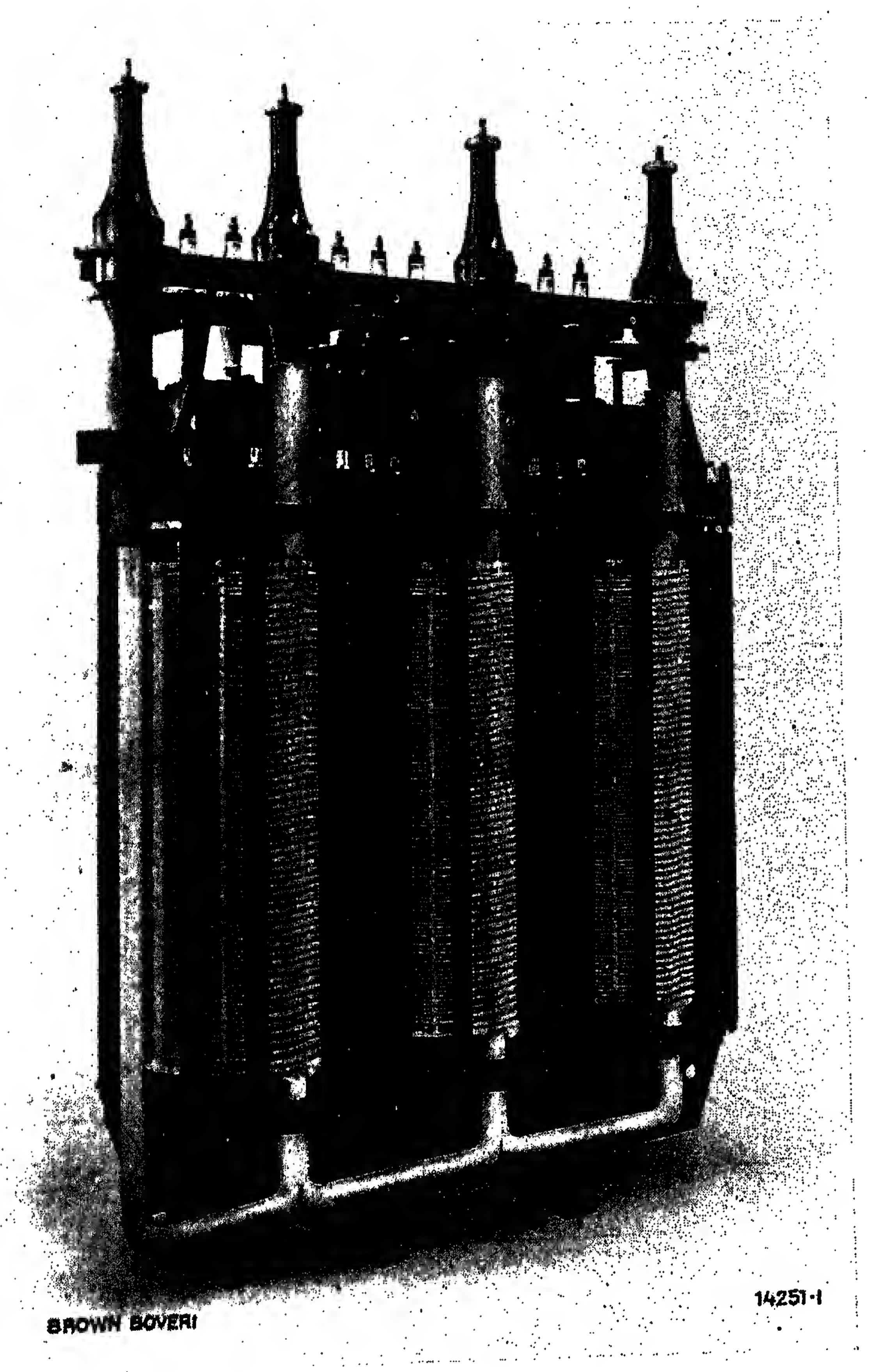


Fig 96. Three single-phase alternators each 10,000 kVA, 15,000 V, $16^2/_3$ cycles, 333 r. p. m., installed in the Barberine Power Station of the Swiss Federal Railways.

BROWN BOVERI

TRANSFORMERS

FOR LARGE OUTPUTS



THREE-PHASE OIL-IMMERSED TRANSFORMER WITH EXTERNAL OIL CIRCULATION.
13'000 kVA, 8600—7535/84'300 V, 50 cycles, delta/star connection.

BROWN, BOVERI & COMPANY
LIMITED

BADEN (SWITZERLAND)

March, 1924

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CONTENTS.

BROWN BOVERI TRANSFORMERS FOR LARGE OUTPUTS.

I. INTRODUCTION.

Apart from the evolution of high-power generating units, the enormous developments in applied electricity, especially in long-distance power transmission, is largely attributable to the fact that the transformer builder has been able to keep pace with increasing requirements and, in many cases, has even been ahead of them. The increase in the output of power stations, the linking up of the latter, and the transmission of large quantities of energy over long distances were the decisive factors in the evolution of the transformer for large outputs. This development is a typical example of how, from small beginnings, and in response to the demands of power-station engineers, the genius of designers has created a type of apparatus capable of meeting the highest practical requirements as to load and pressure. We have not yet reached the culminating point of transformer development, but, in all probability, the design of still larger units than those already built will not deviate greatly from the lines already laid down for large transformer design, to-day.

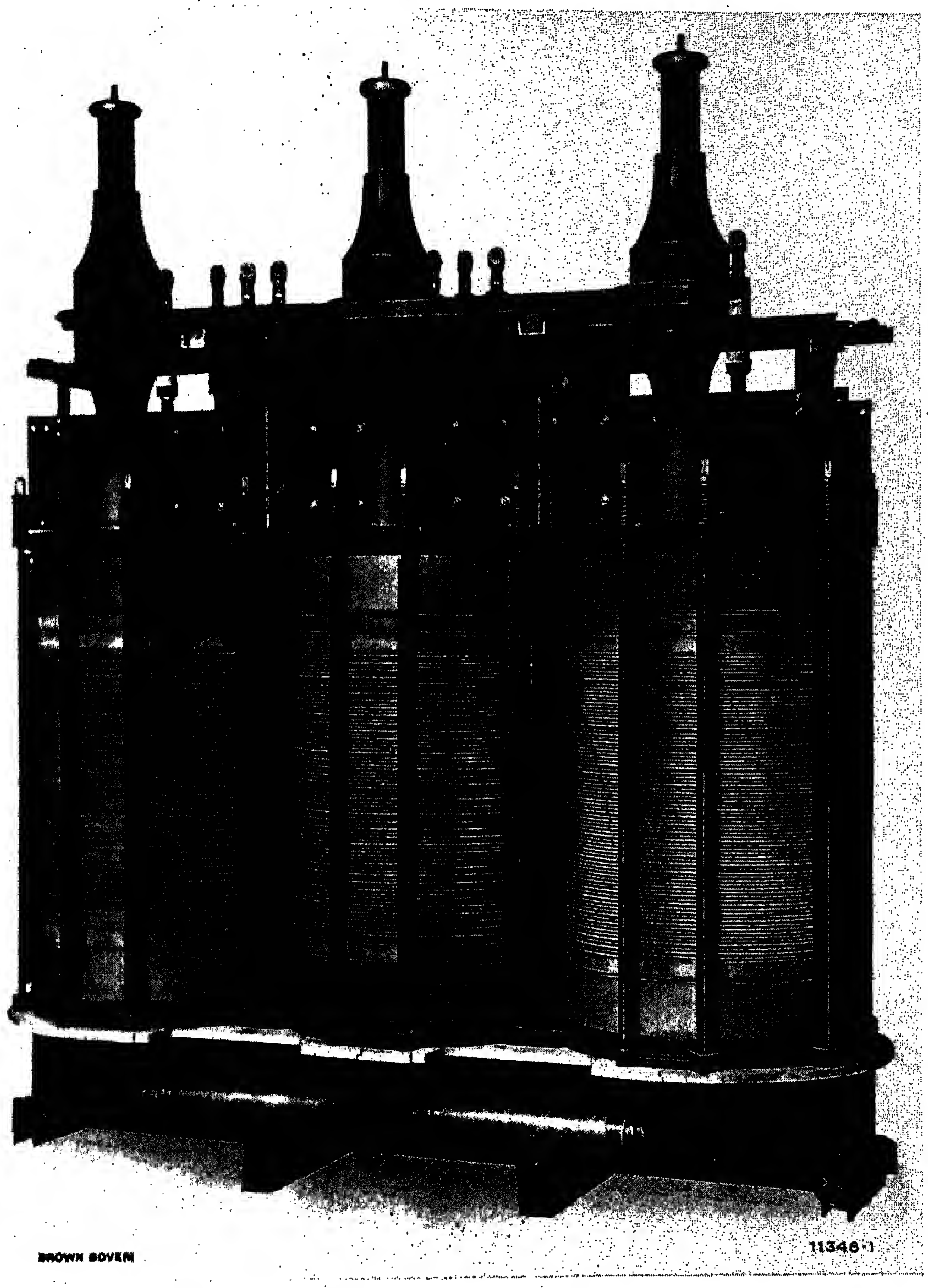


Fig. 1. — Three-phase oil-immersed transformer with external oil circulation, 7000 kVA, 5500—5300—5100/100'000 V, 50 cycles, star/star connection.

The rise in pressure which resulted from the increase in transmission distances led to the exclusive adoption of oil-immersed transformers. These alone meet the demand for stronger insulation and have the further advantage of allowing the heat produced by the unavoidable iron and copper losses to be comparatively easily carried off. Oil-immersed transformers with natural oil cooling were followed by oil-immersed transformers with forced oil cooling.

The linking up of units of large output without any efficient choking device between them, as is customarily practiced to-day in big power stations, puts enormous strains on the mechanical rigidity of the transformers in the event of short circuit, and this necessitates special design. The electrical stresses to be withstood by large transformers, between turns of the winding, neighbouring coils, high and low-tension windings, or the windings and the core, as a result of pressure surges following switching operations or grounding, made imperative an improvement in the old methods of insulation, and the production of new insulating materials. These, in their turn, had to stand up to new and more severe tests of strength and durability. Special methods of impregnating insulation were consequently introduced, together with devices to diminish the electrical stresses.

The magnetic and electrical linking up of different systems may give rise to disturbing phenomena, according to the manner in which linking up is carried out. These disturbances can be eliminated by a correct estimation of the stresses imposed on the material and by proper connections. Finally, one of the most difficult requirements to be met was the necessity for reliability in operation.

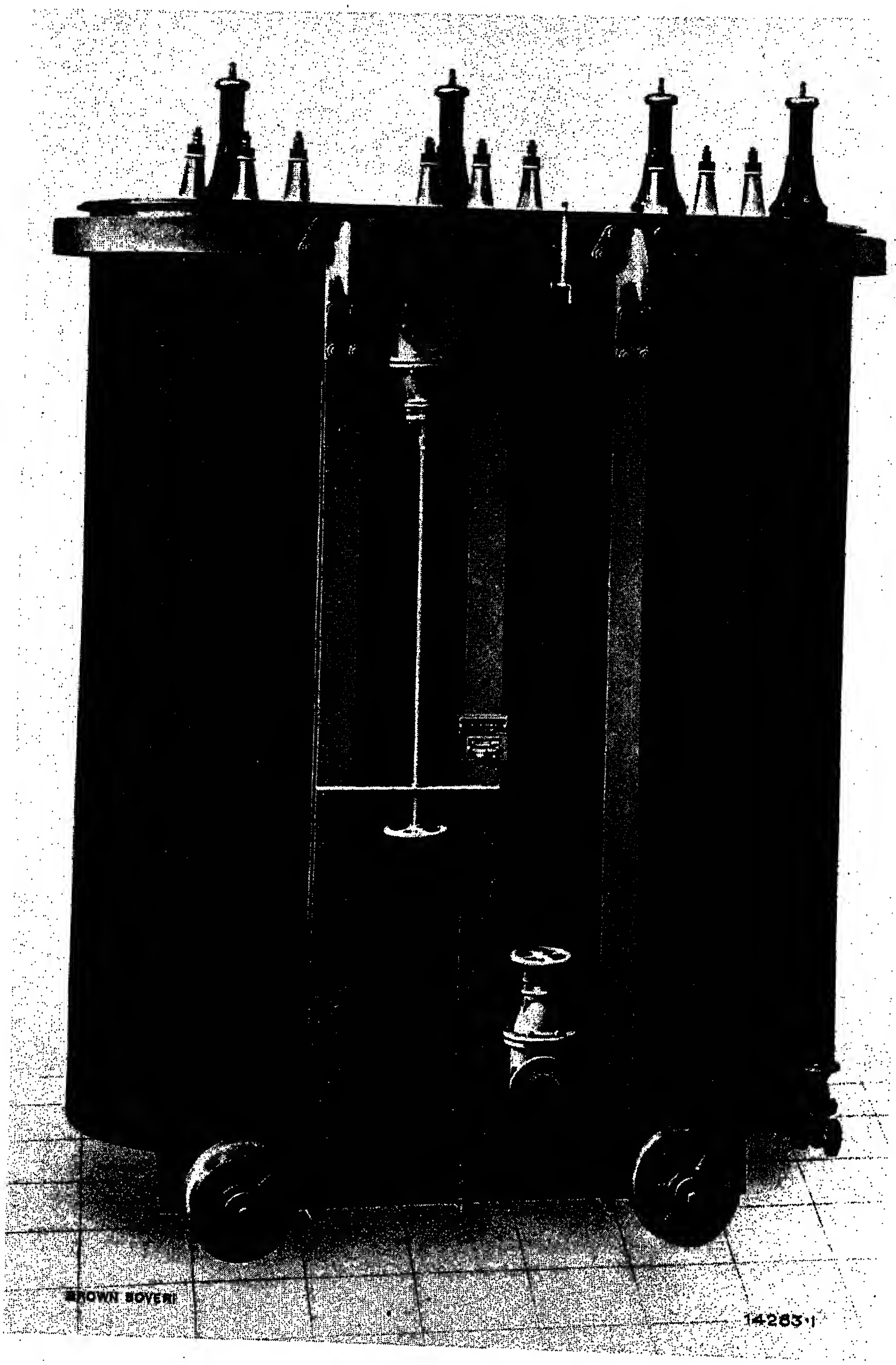


Fig. 2. — Three-phase oil-immersed transformer with external oil circulation, 13'000 kVA, 8600—7835/84'300 V, 50 cycles, delta/star connection.

All these problems could only be satisfactorily solved in the relatively short period during which the high-tension transformer of large output was developing, by exhaustive study, with the help of all available theoretical knowledge, combined with thorough testing and painstaking resear chinto phenomena of apparently secondary importance. This study was materially assisted by the experience gained in manufacture and in the operation of existing plants. The following is a survey of the way Brown, Boveri & Co. attacked these different problems, of the tests made in this connection and the constructive results obtained, and of how the Brown Boveri heavy-load transformer was finally created. Further, some words are said on the behaviour of these units in service.

II. MECHANICAL DESIGN.

1. Oil tanks. The principal qualities necessary in sound oil-tank design for large transformers are: oil-tightness, sufficient strength to stand up to mechanical pressures arising inside the tank during short circuits, and facilities for transport.

The oil tanks are built up of boiler plate. As is well known, special care must be taken to make joints tight against hot oil. The joints in the plating are, therefore, either provided with several rows of rivets or, when possible, butt-welded. The latter method gives very good results. When riveting is resorted to, equally good results are attained by carefully caulking the edges of the plates and the rivets. Fig. 2 shows a welded transformer tank.

The long side of the tank is reinforced by rolled-section stiffeners, which give the desired rigidity against the highest internal pressures which may occur. The stiffeners of the so-called *vacuum tanks* are made especially stout to meet the outside pressure which makes itself felt when the transformer is being dried out under vacuum.

Usually, the tank rests on a movable supporting frame built of section iron and provided with wheels. Thus, when the unit is ready for service, it can be moved along rails. The supporting frame is so designed that the transformer can be moved by the most elementary means such as levers or ratchets. To allow of lifting the transformer by crane, the tank is built with extended wheel axles or with hooks, to which the lifting tackle may be attached. The whole design is so strong that the transformer, when filled with oil, can be raised on locomotive jacks (Fig. 3). In cases where overall dimensions must conform to a railway loading gauge, the tanks can be made in two parts. A special process, which can be applied on site, is used in these cases to make the joint between the two parts quite oil tight.

Units of large output with natural cooling are provided with radiators. These are removable to allow of transporting even the biggest tanks by railway. The radiators are protected against rust by a special spraying process which has proved most efficient in practice. Fig. 11 shows a transformer for 5000 kVA, 60'000/15'000 V, $16^2/_3$ cycles, the tank of which is fitted with radiators.

To allow of running off the oil, a sluice valve is provided which is placed at the lowest point of the tank. This valve also allows of connecting up the oil filter press when the latter is in use, and also of taking samples of oil for tests. Further, the tanks of transformers, built for outside cooling of oil in a separate cooler (external oil circulation), are provided with two sluice valves for connecting up to the piping between tank and cooler.

Fig. 3. — Transformer for 5000 kVA at $16^2/_3$ cycles in front of the Giornico substation of the Swiss Federal Railways, to which it was transported full of oil on one of Brown, Boveri & Co's special crocodile trucks.

2. Magnetic circuit. Recognising that the building of shell-type transformers for large outputs and high pressures would present

difficulties, and that they could not be erected and repaired on site by ordinary means, Brown, Boveri & Co. built their large transformers, from the start, as core types. Subsequent developments during recent years have fully justified this, and nearly all well-known manufacturers have gone over, little by little, to this type of design, as a result of practical experience.

In order to facilitate assembling and dismantling, the laminated cores and yokes of large transformers are not usually interleaved at the joints, butt joints being employed. The surfaces in contact must, therefore, be very carefully finished in order to minimise the humming which occurs when the unit is in operation, and also in order to do away with certain troubles to which these joints are otherwise subject.

According to the conditions under which the transformer is to work, either silicon or high-silicon dynamo sheeting is used to form the magnetic circuit. Non-silicon sheeting is no longer used, on account of its inherently high losses. One side of each metal sheet is covered with a sheet of paper pasted on. High-silicon sheeting is used in transformers which are to be only partially loaded during most of the time, and also in cases where the cost of energy production is high, or when the client purchasing the transformer has to pay on the basis of the energy absorbed by the unit.

The cores and yokes are built up of separate stacks of sheets, the stacks being separated from each other by insulating layers. The groups of stampings forming the core are "stepped" so as to make the section as nearly circular as possible, and thus to obtain a good factor of utilisation. The cores and yokes are held together by stout end plates and massive, insulated bolts. For the end plates a special design is sometimes used with the object of reducing eddy currents in these parts. Tests and calculations on a 13'000 kVA transformer proved that, by using this special construction, the supplementary iron losses, which amounted to 9 kW under normal pressure, were completely done away with.

Defects which may appear in the active iron and which have been termed *iron diseases* are caused by contact between the core and the bolts, and between the sheets forming the core. These contacts form closed electric circuits in the core. The considerable currents induced in these circuits produce excessive local heating which, in its turn, slowly consumes the insulation between the laminations, and this goes on until, finally, the transformer is quite useless. In the manufacture of Brown Boveri transformers, these sources of trouble are avoided by paying great attention to finishing, by consciencious supervision, and by correctly dimensioning and thoroughly insulating those parts most liable to attack. The insulation of the bolts from each separate group of laminations is tested during assembly especially severely. The groups are also tested to make sure that they are completely insulated one from another. Ever since the real cause of the trouble was recognised and guarded against by the above measures, these so-called iron diseases have disappeared. We would add that this form of trouble was familiar, for a certain time, in all big transformer plants and was a cause of much annoyance. It was also discussed and explained in a number of technical articles.

Experience shows that, if the section of the core is to be completely utilised, in transformer units of ever increasing size, the removal of the quantity of heat generated becomes difficult. It was proved that the insulation between the lamination groups and from lamination to lamination was adversely affected after a certain time by excessive heating, and that the insulation was sometimes completely carbonised and became conductive. Tests made by Brown, Boveri & Co. showed that heat conductivity through the layers of sheeting was only about $^1/_{15}$ to $^1/_{25}$ that along their length. Thus, the faces of the end sheets of the core carried off only 4—7 % of the total heat generated in the core. This caused Brown, Boveri & Co. to make cross slits in the cores and yokes, in which cooling oil can circulate. Fig. 4 shows an iron core built on this principle. Ducts are stamped out of the yoke sheeting to serve as inlets and outlets

for the oil circulating in the core slits. To cool the upper yoke, which is bathed in hot oil and which would, therefore, reach a higher temperature than the lower one, cold oil is used in units of very large outputs with external oil cooling. Efficient and thorough cooling of the most inaccessible parts of the iron core section is effected by means of the device above described. This is an advantage which, owing to its influence on the life of the transformer, is not to be underestimated. This method of cooling the active iron of large transformers has been patented by Brown, Boveri & Co.

As said before, the cores and yokes are securely held together so that whatever humming occurs in operation is reduced to the practical minimum; this result is attained by means of clamping beams and bolts. A double hook forms one piece with the upper beam, which makes the lifting of the transformer proper out of the tank an easy matter. The lower beam forms the foot of the transformer.

3. Windings. The following important points must be taken into consideration in dealing with the mechanical design of the coils of transformers for large outputs:—

(a) The mechanical stresses acting radially and axially on the coils when a short circuit occurs.

(b) The temperature rise of the windings under continuous full load and the effect of the temperature on the winding insulation.

(c) The manner in which tappings are made.

Theory and practice demonstrate that circular coils offer the greatest resistance to the mechanical effects of short circuits, because they are exempt from the dangerous bending stresses which are exercised on oval and rectangular coils, and which are especially undesirable when the section of the coil is small. For this reason, all Brown Boveri transformers for big outputs are built with circular coils only.

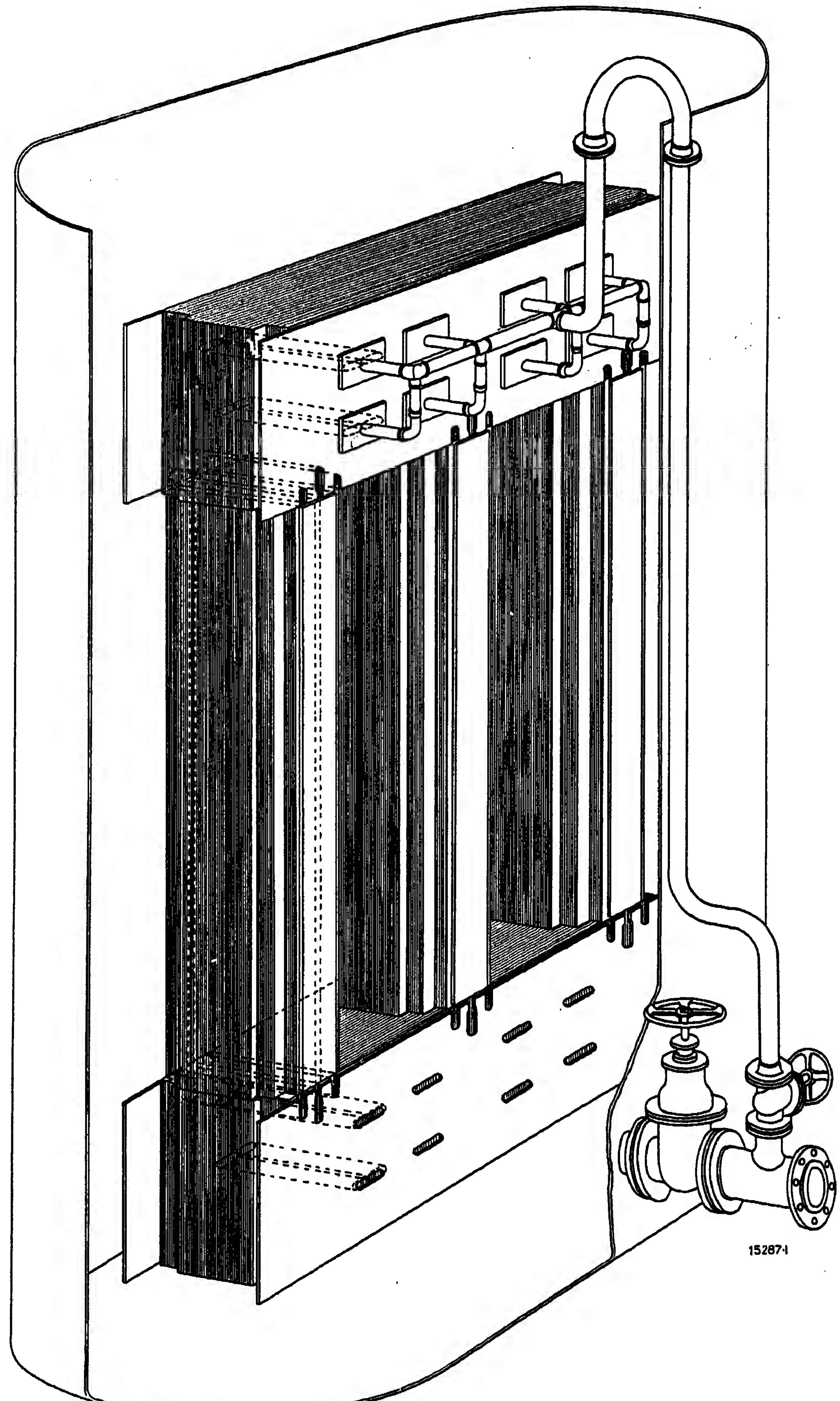


Fig. 4. — Iron core showing slits for the cooling oil.

Calculations showed, for example, that in a three-phase transformer of 16'500 kVA, 8000/135'000 V, 50 cycles, delta/star connected with a short-circuit voltage of 10%, the circular coils were subject to an internal pressure of about 425 tons, during short circuit. It is obvious that only specially built coils can stand up to stresses of this kind. For this reason, Brown, Boveri & Co. devote great care to the mechanical construction as well as to the electrical formation of transformer coils. When a short circuit occurs, the primary and secondary coils may, under certain conditions, tend to shift axially towards each other and against the upper and lower winding supports. This requires specially strong anchoring of the coils with regard to each other and to the upper and lower supports. This axial action of forces becomes very evident when the coils have worked somewhat loose, in the course of time. The coils are then no longer pressed against one another, so that, when the axial pressure suddenly arises, an actual blow is produced. To meet this danger, Messrs. Brown, Boveri & Co. use very stout insulating material for the coils of transformers for large outputs, which does not shrink in oil even after long service. Further, the coils themselves are subjected to a preliminary compression in a hydraulic press before being fitted. The complete windings are held together by a *spring supporting device* patented by Brown, Boveri & Co. This device is composed of pressure rings of cast steel placed above and below the winding and held together by long bolts and spiral springs. In order to distribute the axial pressure evenly between low and high-tension windings, an auxiliary ring is placed between the steel pressure ring and the end distance piece of one of the windings, the position of which auxiliary ring can be set by means of screws. This arrangement was first used in 1909, and has ever since given splendid proofs of its worth. Already in 1910, short-circuit tests on a 600-kVA transformer for 5000/440 V, 40 cycles, gave the results quoted below, which were taken by the client with the help of the oscillograph.

The secondary terminals of the transformer were short-circuited by means of a special bar, while the primary terminals were connected to two alternators, slightly overexcited, and delivering together 12'500 kW. The normal current of the transformer was 63 A.

According to the table reproduced here, the current peak at short circuit was more than 40 times normal.

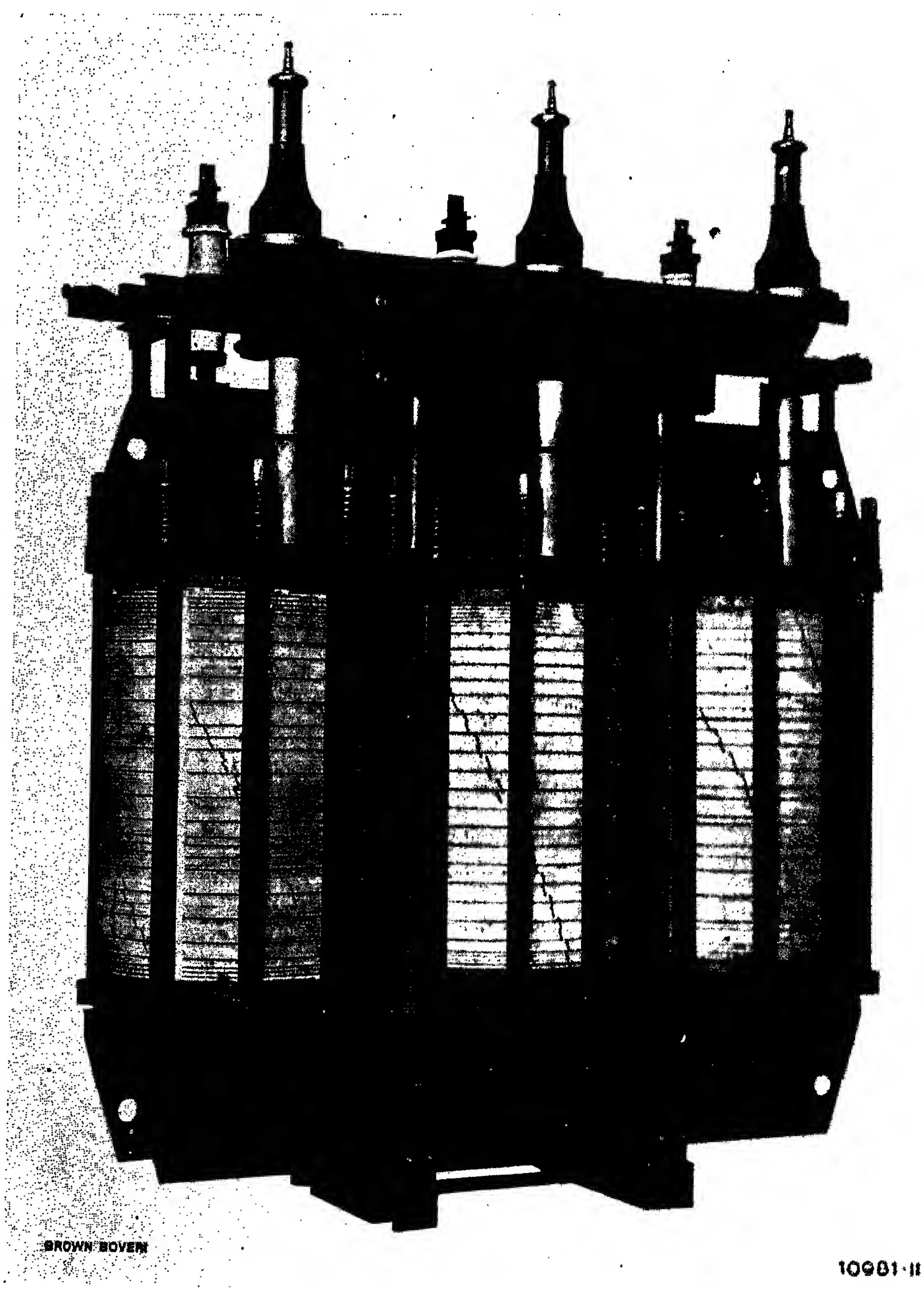


Fig. 5. — Three-phase transformer with external oil circulation, 2000 kVA, 3300 3150 3000/25'000 V, 16⅔ cycles, star/star connection.

Number of periods from commencement of short circuit	First test		Second test	
	Volts	Amps.	Volts	Amps.
Open circuit . . .	5750		5750	
1st. period . . .	4720	2670	4730	2610
2nd. „	4680	2125	4680	2160
5th. „	4620	1950	4560	1950
25th. „	4280	1880	4200	1650
40th. „	4075	1750	3770	1450
50th. „	3700	1565	—	—
Duration in periods	52		45	

Inspection after the test failed to show the slightest change in the transformer. Fig. 5 shows clearly the winding supports described above, as built on a transformer of 2000 kVA, 3300—3150 3000 25'000 V, 16 $^2/_3$ cycles, star connected.

It is difficult to construct transformers for pressures higher than 100'000 V in which the vertical bolts are at a safe distance from the high-tension winding. In a design frequently employed by Brown, Boveri & Co. these bolts can

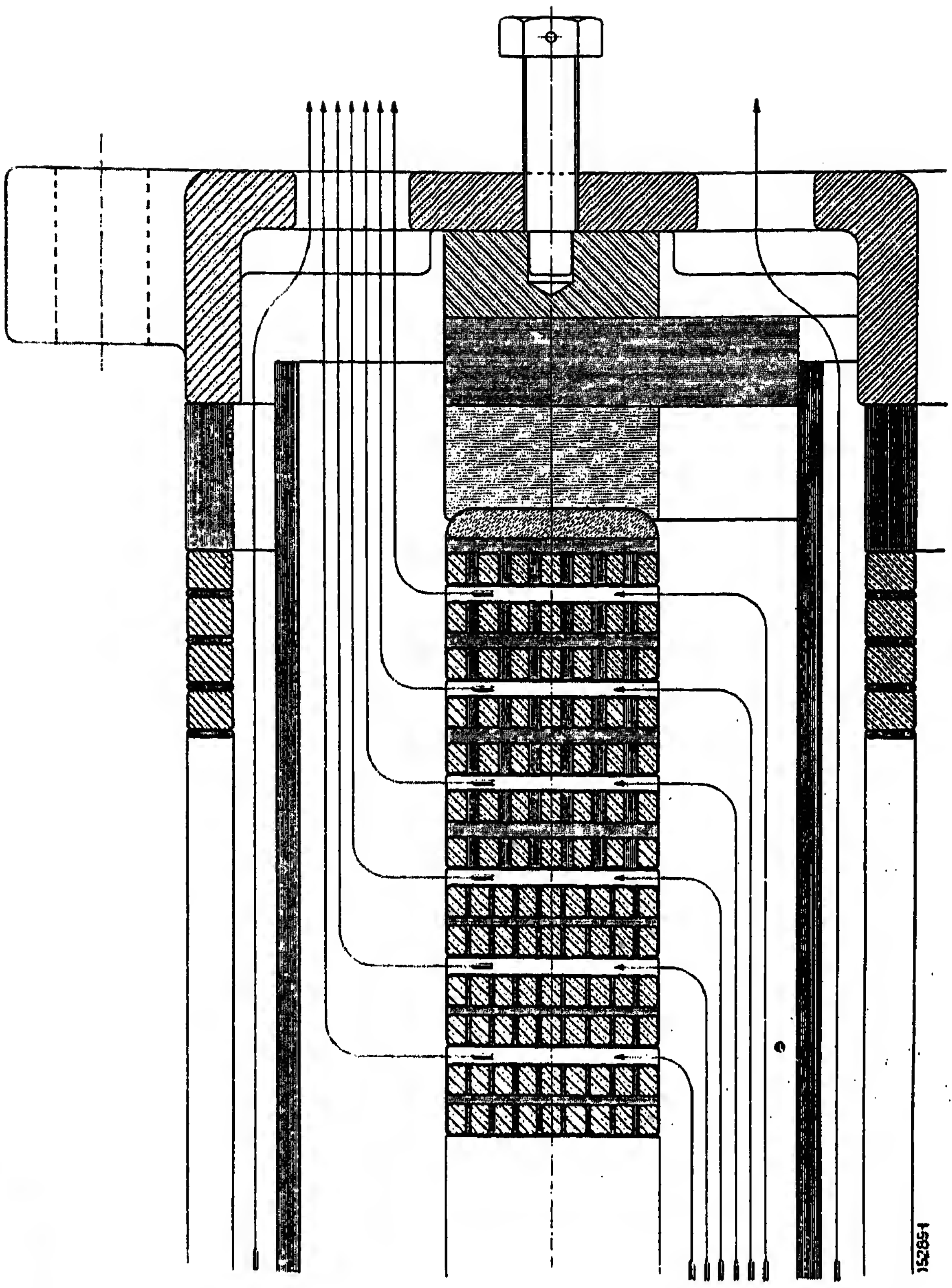


Fig. 6. — Section through a double concentric winding.

be entirely dispensed with. The lower ends of the windings rest on a fixed support attached to the yoke, while the upper ends are secured to a similar support, but through the agency of heavy springs, the pressure on which is exerted by a special balance-arm device, for which a patent claim has been filed.

This design gives the same degree of security in case of short circuits as the first design described.

The temperature of the interior of the windings is a very decisive factor in the length of life of a transformer and it is, therefore, the duty of the builder to arrange the windings so that no excess heating of any part is possible. This is a comparatively easy matter with layer windings, because the coils are formed of flat copper, wound edgewise and in contact with the cooling oil both in side and outside. In high-tension windings of Brown, Boveri transformers for large outputs, wide slits are provided between every second double coil. Fig. 6 shows the arrangement

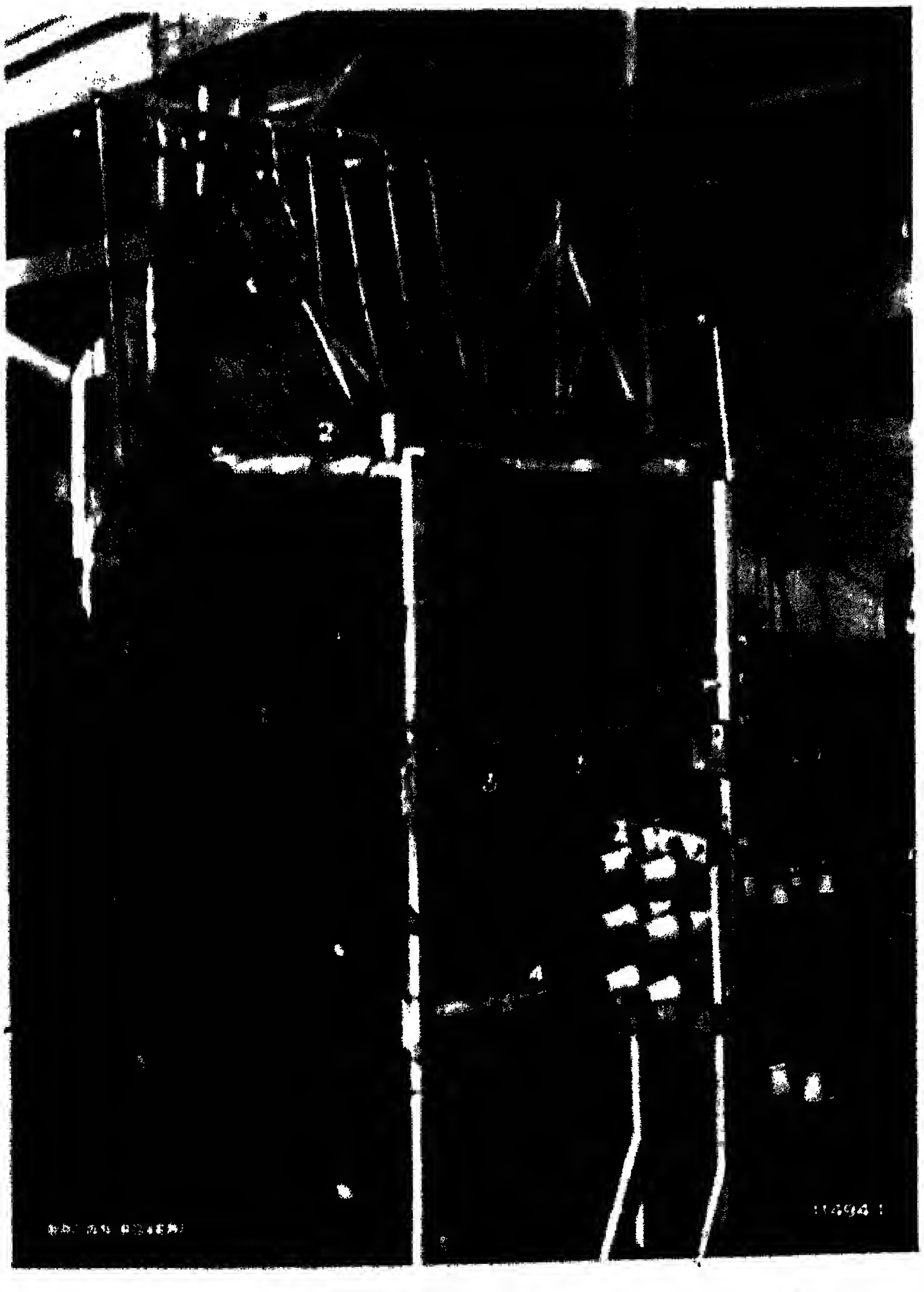


Fig. 7. Arrangements for heating test on a 5150-kVA transformer showing switch for thermo-couples.

of the oil slits or ducts between the core, the low-tension coils, the insulating sleeve, and the high-tension winding, and between the different high-tension coils. By this arrangement of cylindrical windings, most efficient cooling of the innermost parts of the coils is assured. Very careful tests made on a 5150-kVA transformer showed a maximum temperature rise at the warmest spot of 60° C. above the cooling-water inlet temperature, while the mean temperature of the whole winding was only 8° C. lower. The longer life both of insulation and of oil, ensured by these low temperature rises, is a very great advantage, the importance of which is rarely sufficiently realised. Fig. 7 shows the arrangement employed for heating tests conducted on a 5150-kVA transformer, in the transformer testing department at the Brown Boveri works in Baden. The transformer was heated by communicating to it quantities of heat equal to those produced by iron and other losses at different loads. In this way, the same conditions as occur in service are exactly reproduced. This method is used in cases where the size of the transformer or its pressure ratio makes a direct load test impossible. In the case in question, thermo-elements to the number of 55 were lodged in the windings, in the core and immersed in the oil. Special mercury thermometers were used to check the temperatures given by the thermo-elements. This test, carried out with the greatest care, gave an exact illustration of the temperature conditions in the transformer when under load and provided valuable data for the calculation of units for large outputs.

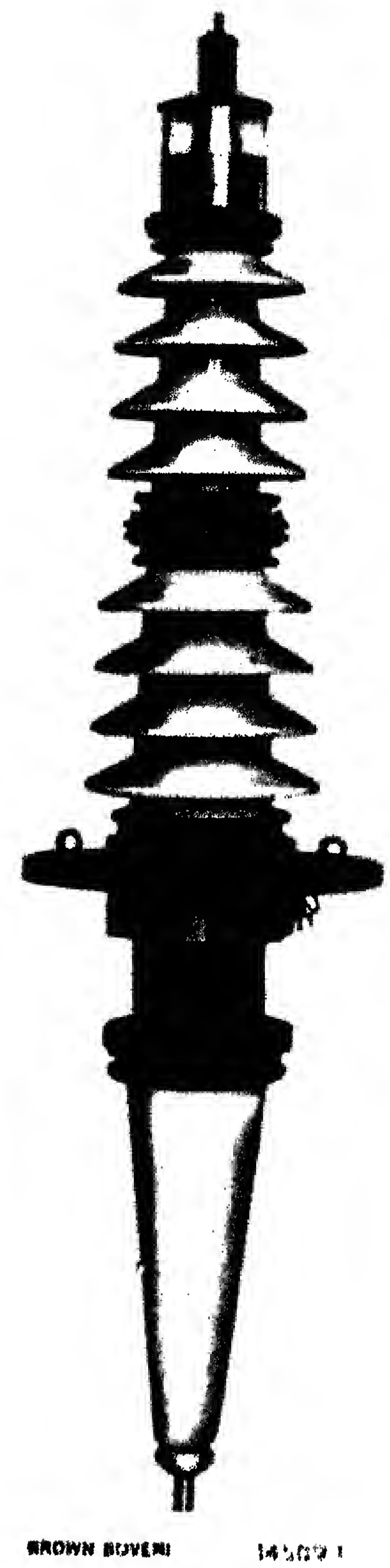


Fig. 9.
Transformer bushing for 150'000 V, 350 A.

4. Tappings. In practice a change in pressure ratio is often necessary, that is to say, the incoming or outgoing conductors have to be connected to tappings. According to the percentage of pressure change required, smaller or greater sections of winding must be cut out, thus affecting the symmetry in ampère-turn distribution between primary and secondary windings.

For this reason, correspondingly greater axial forces on the individual coils come into play than is the case when primary and secondary windings are exactly superimposed. For this reason, tappings should only be added to the windings of transformers of large outputs when absolutely necessary.

In the diagrams of connections shown in Fig. 8 the three principal arrangements of tappings as executed by Brown, Boveri & Co. are shown: (a) is the simplest arrangement, while by using those shown in (b) and (c), that is to say, by cutting out coils in the centre of the winding, the axial short-circuit forces are considerably reduced. The tappings themselves are either brought out above the cover to single-pole or multi-pole terminals, or else the change of connections is made on the coil ends, which are brought to the surface of the oil, the cover being removed.

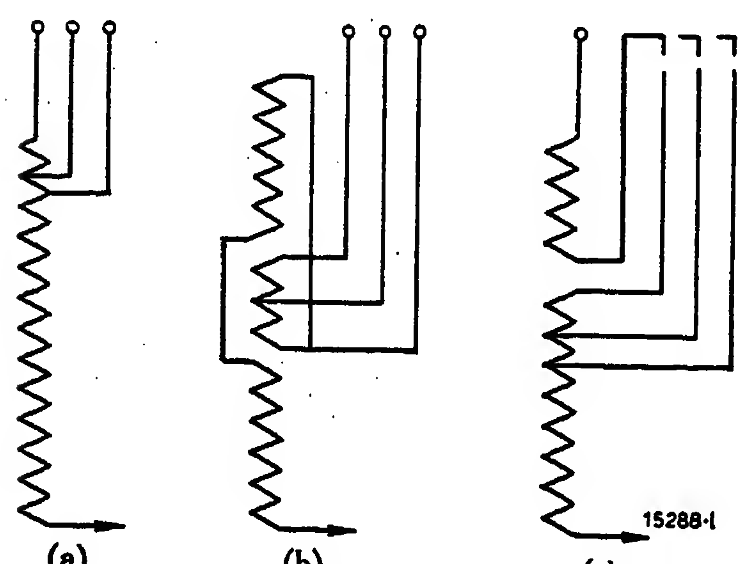


Fig. 8. — Three methods of arranging tappings.

For tappings on the high-tension side, Brown, Boveri & Co. have designed and patented a tapping switch, by means of which the passage from one tapping to another is graduated in steps. This switch is built into an insulating cylinder which contains a number of so-called contact rings corresponding to the number of tappings. Contact between any two rings is made by several metallic spheres inside the cylinder in the same horizontal plane and pressed outwards radially by springs. The sphere contacts can be changed over to the various tappings by moving them vertically when not under tension. The tapping switch is protected outwardly by protecting rings and a metal cover. It is

fastened to the cover of the tank by an insulating tube and can be operated from without by means of a handwheel with an indicator giving its different positions.

Thorough tests have proved that this type of switch can be built for pressures of over 100'000 volts. Thus Brown, Boveri & Co. have solved in a simple, practical, and reliable manner the problem of tappings. This switch was first used on seven single-phase outdoor-type transformers each for 4330 kVA output, 78'000—72'600—70'800—68'900—68'900—67'100—65'300/52'000—50'700—49'400—48'100—46'800 V, frequency 50, with star/delta connections.

5. Transformer bushings. Brown, Boveri & Co. use porcelain insulators as well as Bituba and Bakdura for this purpose, according to whether the transformer is of indoor or outdoor type. Insulators of Bituba and Bakdura are made in their own works and subjected to careful supervision as to the quality of raw materials used, process of manufacture, and finishing. The Bakdura insulators consist of a metallic tube on which Bituba is wound and over which a Bakdura body is drawn. Great attention is given to the testing of Bakdura insulators before they are built into the transformer. These tests include a durability test with regard to heating, during which the losses are measured by means of a high-tension wattmeter built by the firm specially for this purpose, and also a corona test. The former test lasts two hours, during which the temperature rise in the interior is measured exactly, the insulator being under approximately double the service pressure. If the material be free from defects, the temperature rise should not be greater than 15° C. The corona test takes place in a dark chamber. No corona effects should appear when the insulator is subjected to the test pressure specified. Flashover and breakdown tests under oil were carried out on a series of insulator types. Practical experience during the last years with these insulators is the best proof of the reliability of the material, of the manufacturing process, and of the tests employed.

Porcelain insulators are used in transformers for high pressures above 100'000 volts (Fig. 9). These insulators are composed of the following parts: a metal tube on which Bituba is wound, the upper and lower porcelain bodies, interior sleeves of Bituba, the metal flange with two rings for securing the insulator in position, the expansion receptacle and the upper and lower oil-tight closing pieces with the terminals. The whole insulator is filled with oil, the expansion of which on heating is provided for by the expansion vessel placed on the top of the insulator. This glass vessel also allows of inspecting the level of oil in the insulator. To prevent dust particles from forming bridges on those parts most subjected to stress, sleeves of Bituba are built into the insulator. In order to be able to test these bushings independently of the apparatus to which they belong, the high-tension test room was installed with special equipment which enables complete tests to be made in the dark, under rain and flashover conditions for pressures up to 500'000 volts. Repeated tests gave the following mean results:

Rated pressure of insulator	65	80	110	150 kV
Flashover when dry . . .	230	270	330	400 kV
Flashover under rain . . .	150	180	220	270 kV
Breakdown (calculated) . .	240	330	470	660 kV

Fig. 10 shows a 150-kV insulator under rain at the moment of flashover (280 kV).

Fig. 10. — Flashover of a 150'000-V oil-filled bushing under a rainfall of 2·5 mm per minute and a test pressure of 280'000 V.

6. *Transformers for outdoor service.* The great increase in building costs led to the erection of outdoor stations and produced a demand for transformers which could work under these conditions. While the transformer proper remained the same as described in the foregoing paragraphs, the cover, the expansion chamber—or conservator—mounted on the cover, and the bushings had to be specially designed. Fig. 11 shows a transformer of this kind, built for natural cooling and for 5000 kVA, 60'000/15'000 V, 16²/₃ cycles. The cover is formed of boiler plate and designed like a roof so that water can easily run off. It is securely bolted to the upper rim of the tank and is made oil tight by a special process. This is necessary because, with outdoor transformers, the tank is completely filled with oil, which is under a certain pressure on account of the use of a conservator. The object of the latter is to take up the expansion of the oil at high temperatures, and also to prevent the ingress of damp to the transformer. As the only contact between air and oil takes place in the conservator where the oil is cold, oxidation of the oil is reduced to a minimum. The conservator is airtight except for a breather tube containing a hygroscopic substance, so that, although the oil surface rises and falls according to temperature, it is always under atmospheric pressure and is only exposed to dried air, condensation of moisture inside the transformer being thus rendered impossible. Further, there is no circulation of air in the transformer, because the only air which enters the tank is that necessary for what may be termed the breathing of the transformer. As the transformer is absolutely air tight and the cover securely bolted down, a safety valve is used. This device permits of compensating pressure differences inside the transformer; small pressure oscillations are compensated by the tube connecting the safety valve to the expansion chamber, while sudden, big pressure increases cause the cover of the oil-sealed safety valve to rise.

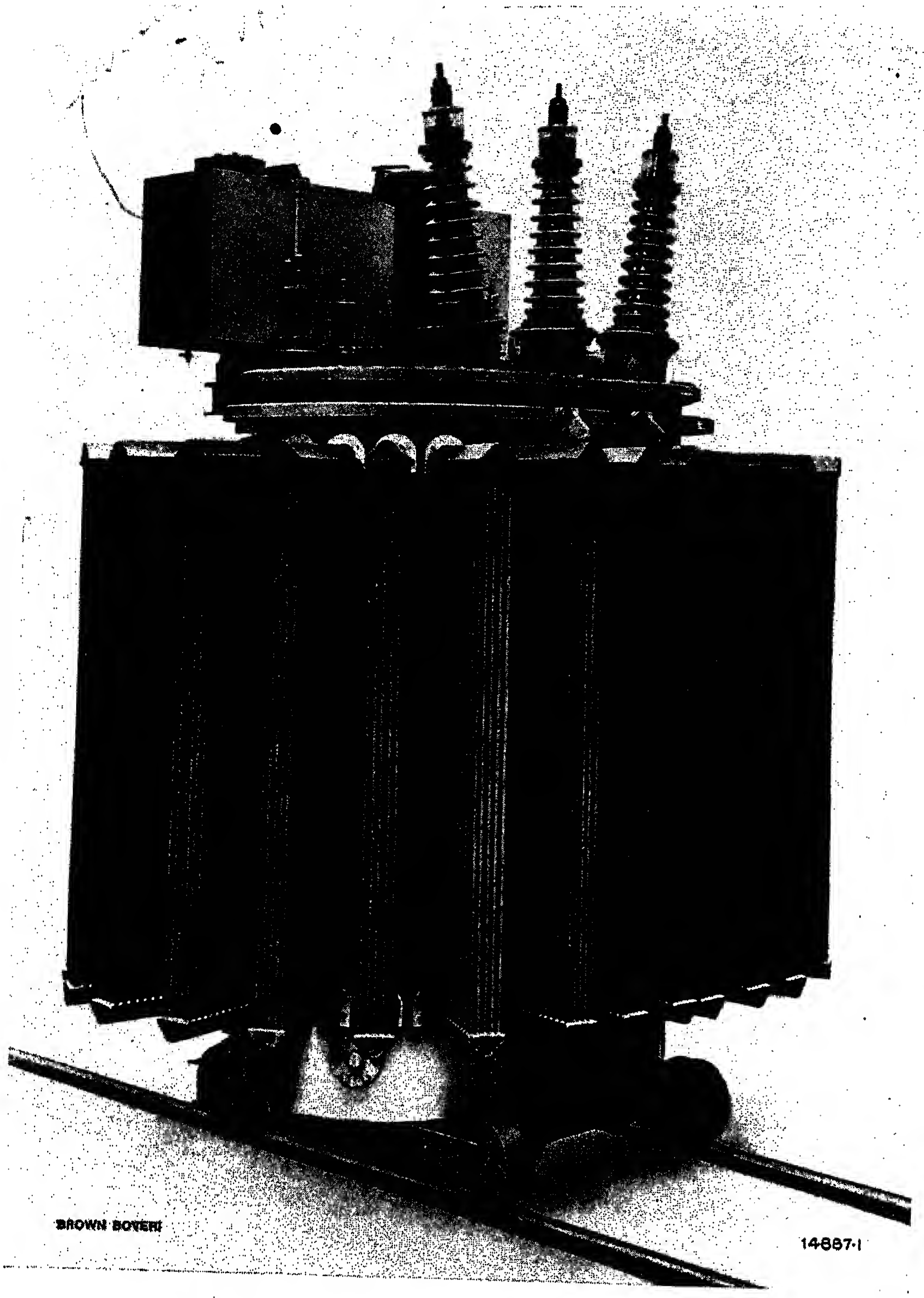


Fig. 11. — Single-phase outdoor transformer with natural cooling, 5000 kVA, 60'000/15'000 V, 16²/₃ cycles, corresponding to a 15'000-kVA unit at a frequency of 50 cycles. (The centre point of the high-tension winding is brought out.)

7. *Transport facilities and erection on site.* To facilitate transport, the transformer tanks are provided with lifting hooks and rest on a movable base frame, as was explained at the beginning of this chapter. In order to secure the transformer proper, the Brown Boveri units for large outputs are, further, provided with special bolts which allow of fixing the active part securely in

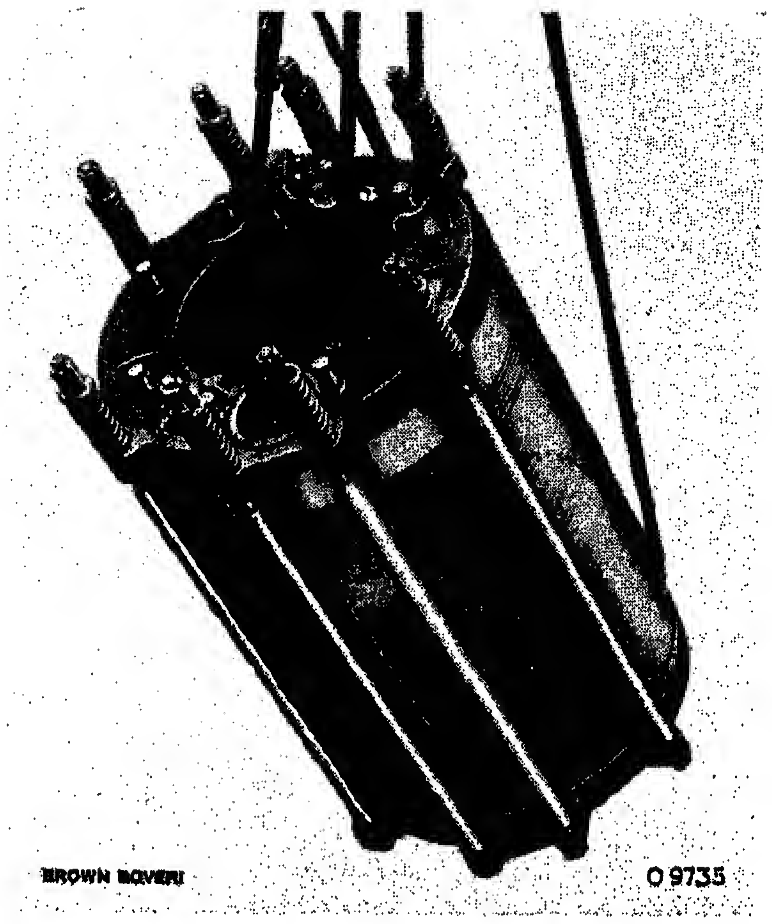


Fig. 12. — Winding of a 3000-kVA, 8000/48 578-V, 50-cycle transformer, showing patent spring support.

the tank. The lower bolts can be adjusted from without as is seen in Fig. 13. Experience has shown that, whether the complete transformer is transported by rail or moved on its wheels, this method of securing the transformer in the tank is most efficient. The transformer is despatched filled with oil, whenever possible. Thus erection is made easier, and the drying out of the oil on site is avoided, which means a big saving of time and, therefore, of money.

If, on account of special transport conditions, such as bad roads or marine transport, the transformer must be despatched in parts, the Brown Boveri design for large outputs, that is, the core type with yokes bolted to the cores and concentric windings, make for the simplest erection on site. The patented method of supporting the windings allows of placing the complete high and low-tension windings in position without breaking the coil connections. Fig. 12 shows a winding of this kind. Further, this design permits of keeping a complete core winding in oil as a spare, which, if required, can be put in position in the easiest manner possible. The transformer is therefore ready for service again in a very short time. Special care is taken to make the fitting and dismantling of the bushings an easy matter. Generally, these bushings are removed during the transport of big units. The Brown Boveri design of bushing allows of easy and expedious erection on site. Section VIII contains further particulars on this subject.

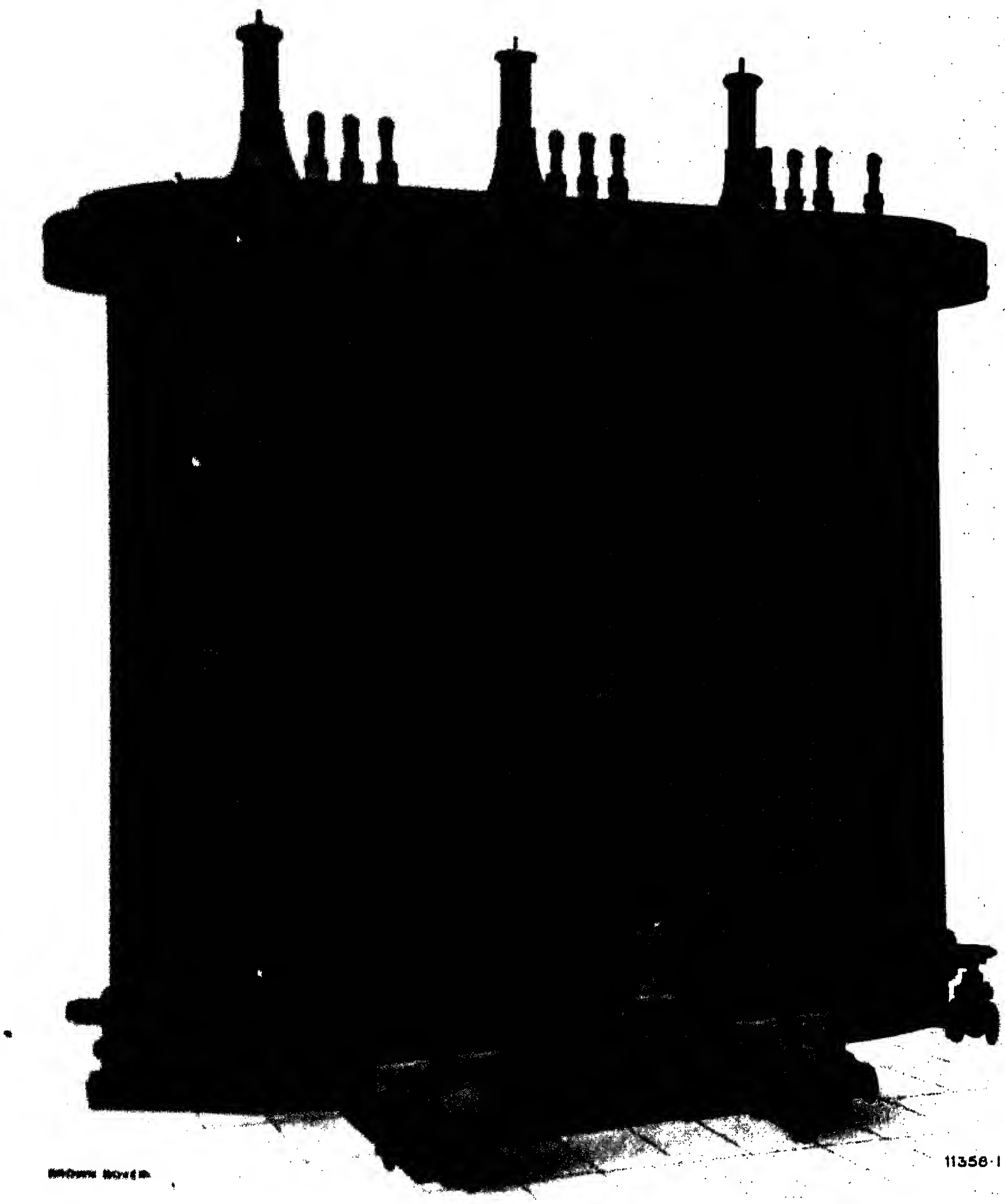


Fig. 13. Three-phase oil-immersed transformer with external oil circulation, 7000 kVA, 5500/5300/5100/100 000 V, 50 cycles, star/star connection.

III. ELECTRICAL FACTORS IN DESIGN.

The design of a transformer of a given iron-core section is definitely fixed, from the electrical point of view, when the flux density in the core and current density in the conductor have been decided on. The following table shows the factors dependent on the choice of flux and current densities:

1. Factors dependent on the flux density.

The price	The no-load losses
The weight	The temperature rise in the core
The dimensions	The no-load current
The short-circuit pressure	The switching current.

2. Factors dependent on the current density.

The price	The copper losses
The weight	The temperature rise in the copper
The dimensions	The overload capacity.
The short-circuit pressure	

To improve the factors in the left-hand column, the tendency is to make the flux and current densities as high as possible, but this again is limited by the factors in the right-hand column. Careful calculations show that, once the flux and current densities have been settled, conditions dependent on them only deteriorate slowly if the flux and current densities decrease, while, if the latter be raised above the values fixed, the conditions become worse so rapidly, that such increase must immediately be stopped.

In transformers for large outputs, each of the above factors becomes a problem calling for careful study. Early recognition of the true facts of the case caused Brown, Boveri & Co. to carry out exhaustive researches with the object of determining the practical limits which should be set for the flux and current densities. These investigations were not confined solely to theoretical considerations, but the actual working conditions were studied with the aid of models and finished transformers.

In the following paragraphs, we enumerate some of the guiding principles and conclusions which have endowed Brown Boveri transformers with a deserved name for reliability in service.

1. Higher harmonics in the magnetising current. In the first place, we desire to show the difficulties encountered in increasing the induction, and the consequences of such an increase. It is obvious that, when the flux density is raised, the losses and no-load current increase rapidly and call for special attention. With regard to the question of heat dissipation, we would refer to what was said on page 6, where the yoke and core design was discussed, and would recall the very efficient Brown Boveri method of cooling the core by slits carrying oil to the hottest parts. The heating can, of course, be reduced by using high-silicon sheeting for the core, but its use results in no-load currents which are, according to the flux density, from 50 to 100% heavier than those corresponding to ordinary sheeting. These heavy no-load currents are not only undesirable on account of the losses and poor power factor entailed, but fully as much on account of the higher harmonics which appear in the magnetising current as a consequence of the higher iron satura-

tion. The following figures give a picture of the composition of the magnetising current of high-silicon sheeting. Of these, Figs. 14a and 14b are based on a magnetising-current curve with a flux density of from about 13'000—15'000, while Fig. 14c takes into account the effect of the hysteresis loop with a maximum flux density of 15'000. The strong influence of the saturation on the production of higher harmonics is visible in these figures and is very clearly shown in the following table, which gives the amplitude of the higher harmonics as a percentage of the first or fundamental harmonic.

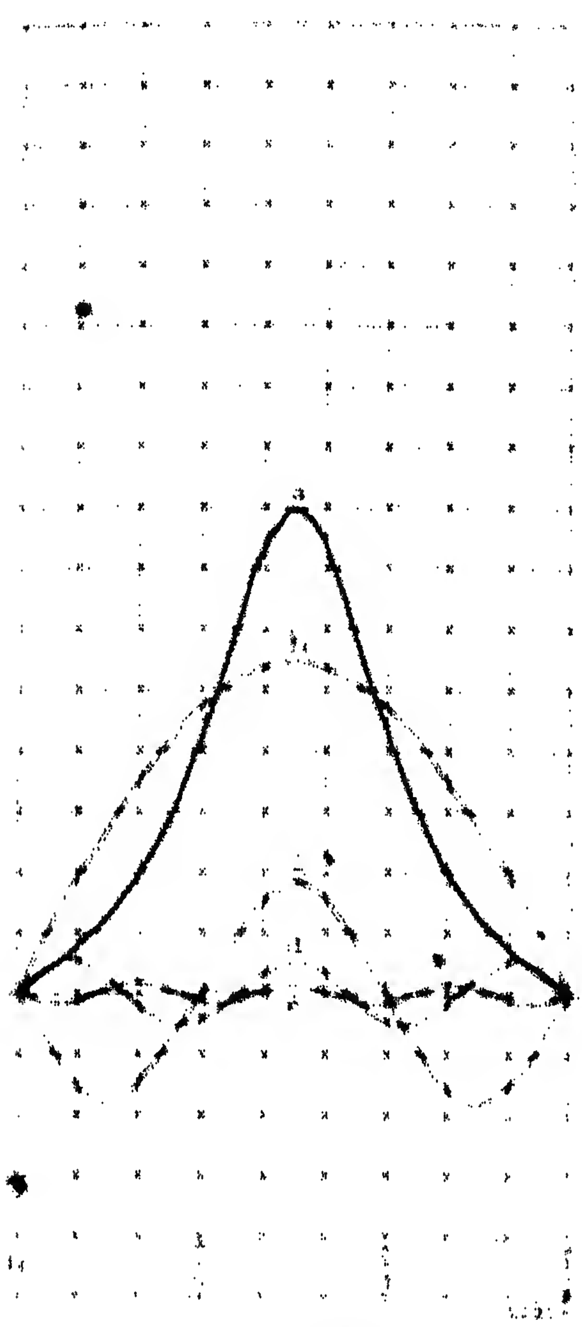


Fig. 14a.
Magnetising current with low flux density.

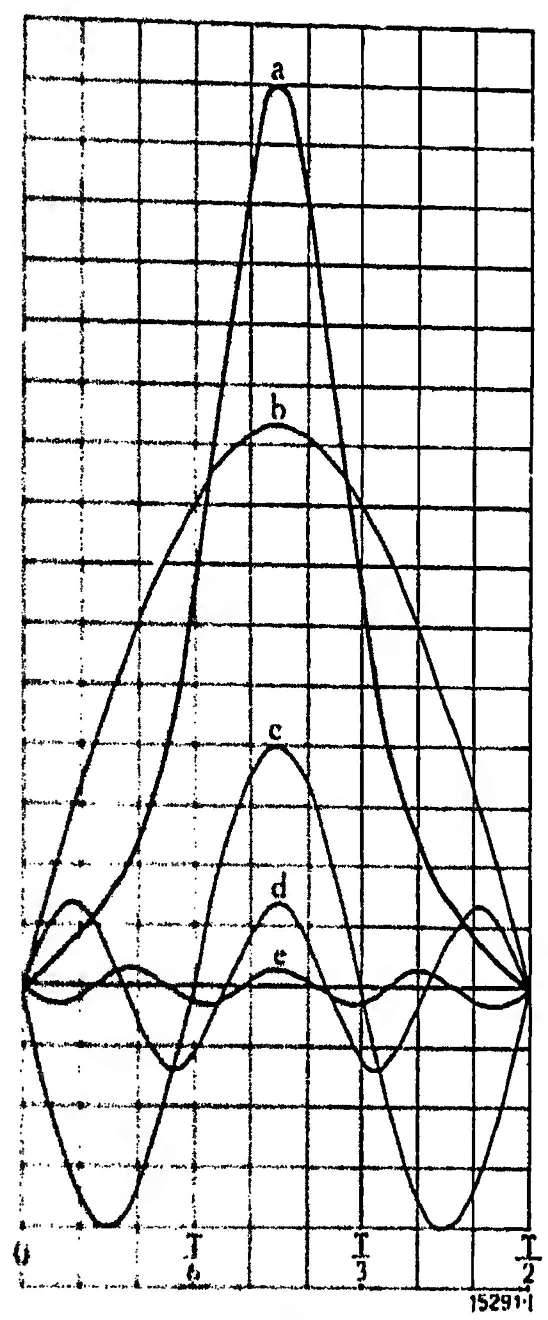


Fig. 14b.
Magnetising current with high flux density.

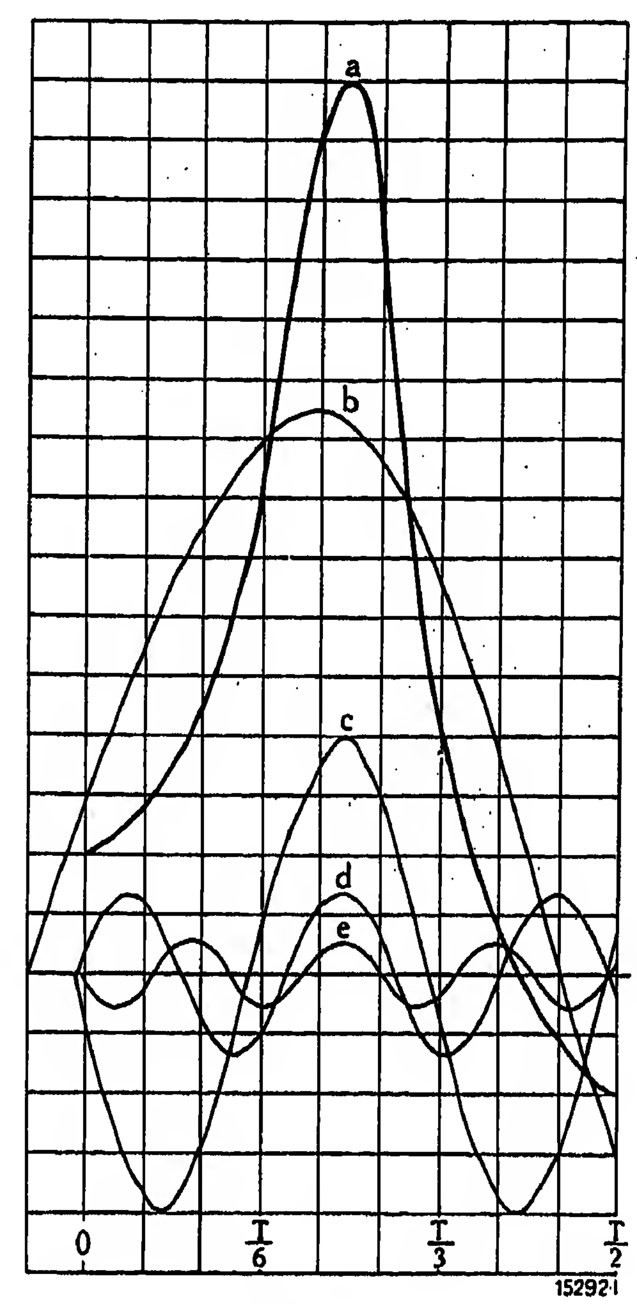


Fig. 14c.
Magnetising current with high flux density, taking hysteresis into account.

a. Magnetising current. b. Fundamental harmonic. c. Third harmonic. d. Fifth harmonic. e. Seventh harmonic.

AMPLITUDES OF HIGHER HARMONICS OF THE MAGNETISING CURRENT AS PERCENTAGES OF THE FUNDAMENTAL HARMONIC CURVES.

	J_1	J_3	J_5	J_7
Flux density 13'500	100 %	34 %	10 %	3,2 %
" " 15'000	100 %	43 %	15 %	3,7 %

In the above table, J_1 the fundamental harmonic—is taken as 100 % for both values of the flux density, and the other harmonics, J_3, J_5, etc., are expressed as percentages of J_1 in each case.

GROWTH OF THE AMPLITUDES THROUGH INCREASE OF THE FLUX DENSITY.

	J_1	J_3	J_5	J_7
Flux density 13'500	100 %	100 %	100 %	100 %
" " 15'000	170 %	220 %	250 %	200 %

In the second table, the amplitudes of all the harmonics when the flux density is 13'500 are taken as 100 %, the corresponding percentage being given for each harmonic with a flux density of 15'000.

A comparison of Figs. 14 a and b with Fig. 14 c shows the influence of the hysteresis loop which, as a result of the losses, causes a slight diminution of the phase displacement. At the same time, it is seen that the effect of the hysteresis losses on the higher harmonics is very small indeed.

It was, now, of primary importance to discover if the induction adopted by Brown Boveri & Co. for their transformers was well chosen with regard to the damping effect presented by big distribution systems, and if the higher harmonics did not grow to an extent undesirable in practice.

Theoretical calculations backed up by practical tests in existing plants all led to the conclusion that the induction chosen was in every way satisfactory and that the small higher harmonics, which cannot be completely suppressed, were in no way a factor of danger for the distribution system.

2. The influence of the method of connection on higher harmonics. The influence exercised by the method of connection on the formation of higher harmonics, if the terminal pressure be taken as being an absolute sine curve, is worthy of attention and has been thoroughly studied, but it is nevertheless advisable to keep this factor in mind when studying either new designs or new plants.

The higher harmonics in the current curve, of single-phase transformers, due to the magnetisation of the iron core, are very apparent. The oscillogram in Fig. 15 shows them up clearly and the shape of the current curve coincides with Fig. 14.

Three-phase transformers possess the interesting property that, according to the method of connections, the third harmonics of the current do not flow in the outside system connected to the transformer. The principle methods of connection are:

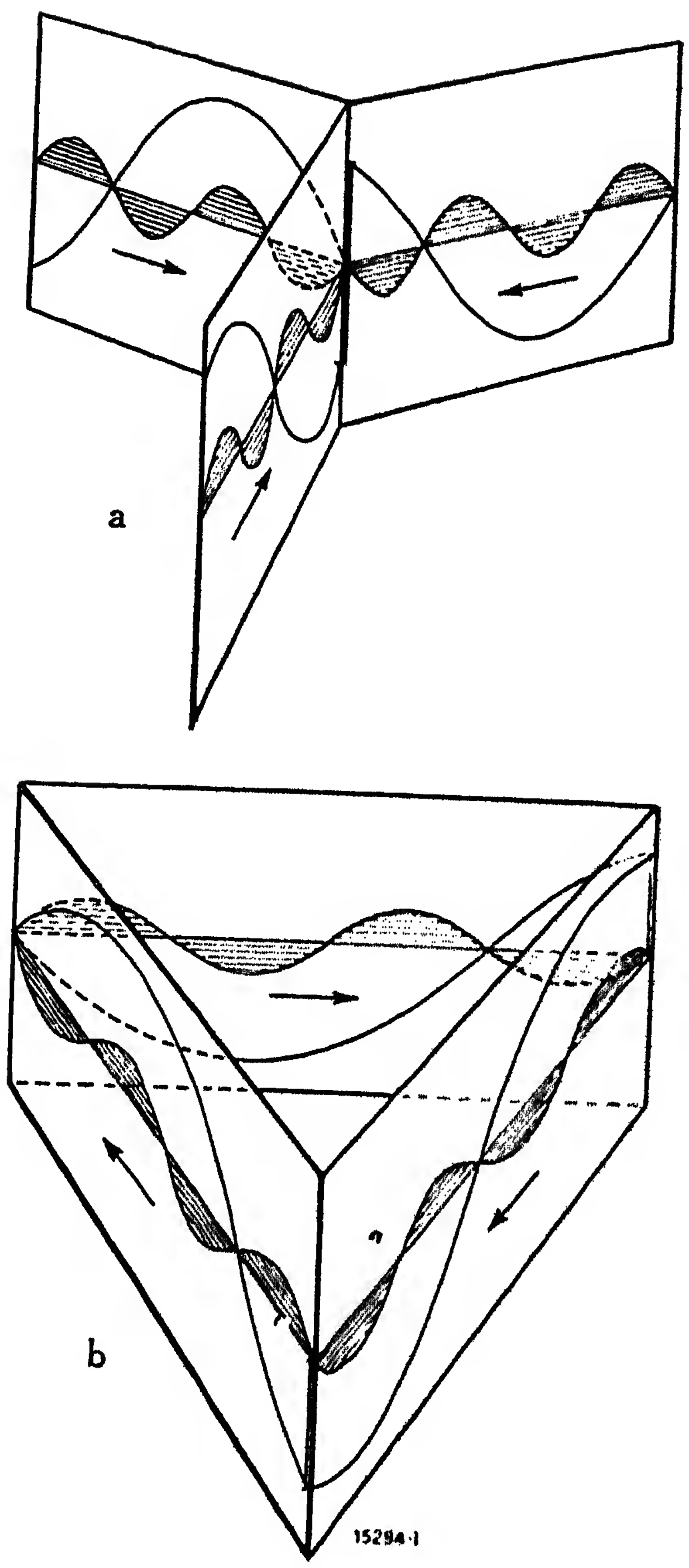


Fig. 16. Diagram illustrating the third harmonics.

a. With star connection.
b. With delta connection.

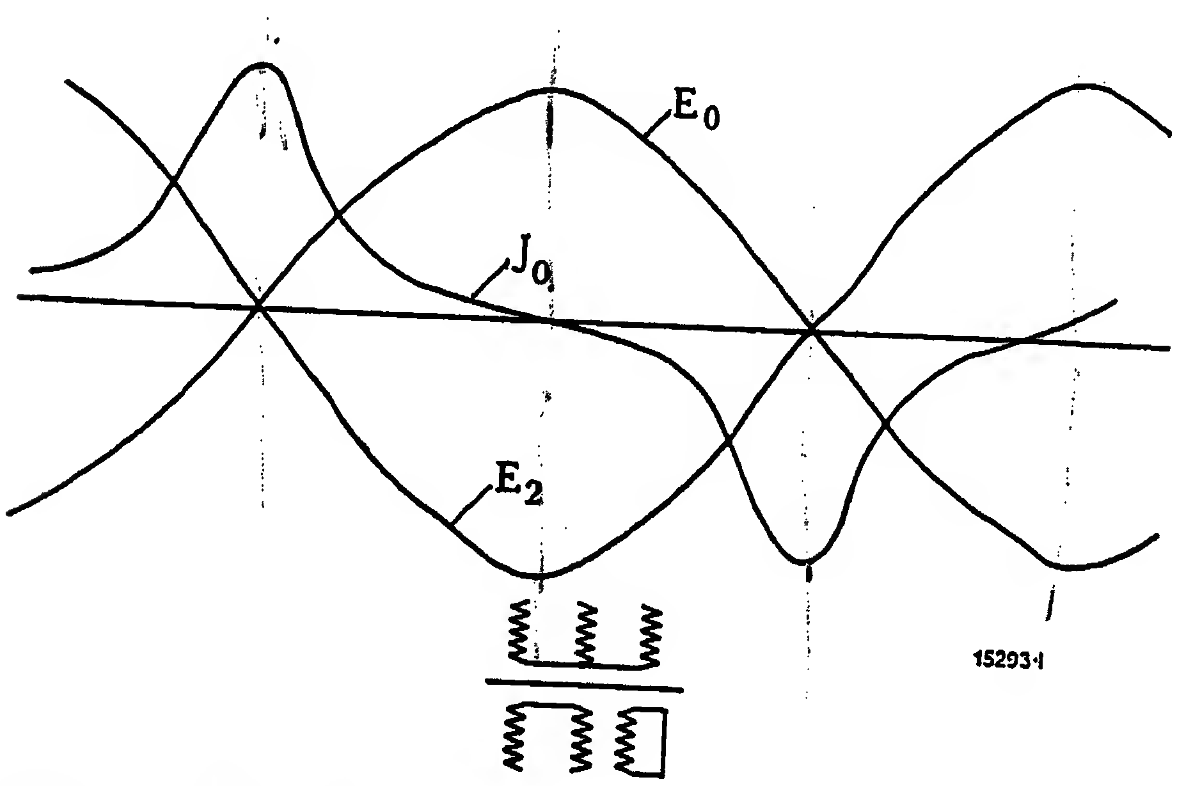


Fig. 15. — Oscillogram taken from a 300-kVA, 433/2900-V, 50-cycle transformer with the flux density increased about 20 %.

J_0 and E_0. Current and voltage on low-tension side.
E_2. Voltage on high-tension side, connected single phase.
$E_0 = 600$ V.
$J_0 = 32$ A.
$E_2 = 6980$ V.

(a) Star connection with the neutral point not earthed.

(b) Star connection with neutral point earthed or connected to a neutral wire.

(c) Zigzag, connection with neutral wire.

(d) Delta connection.

All the above methods are practised with three-phase transformers or with banks of three single-phase transformers.

The behaviour of the third harmonics is best made clear by Figs. 16 a and b. Fig. 16 a shows the three phases connected to a neutral point and Fig. 16 b shows the three phases connected in delta. The instantaneous values of pressure and current in the three phases are given by the sine waves, which are taken as moving

at constant speed in the direction of the arrows. The instantaneous values are then read on the straight line formed by the intersection of two planes. In Fig. 16 a, this is the line through the neutral point, and in Fig. 16 b, it is the line at any of the three apexes.

Fig. 16 a shows that, at the neutral point, the third harmonic has the same value in all three phases. The pressure values of the third harmonic of any two phases are thus opposed to each other, so that, even when they are present in the phase pressure, they do not appear in the pressure between phases. Thus, the current due to the third harmonic of the pressure can only flow when there is a closed circuit over a neutral wire or earth, as in the methods of connection mentioned second and third in the foregoing list.

The third harmonic in the pressure between phases does not appear in the oscillograms of Figs. 17 or 18. The distortion visible in the curves is due not to the third, but to the fifth harmonic. In the current also, the fifth harmonic is strongly marked, while the third harmonic does not show up.

If delta connections be made, as in Fig. 16 b, it is clearly seen that the third harmonics are at all moments equal to one another at all three apexes of the triangle. It will also be seen that

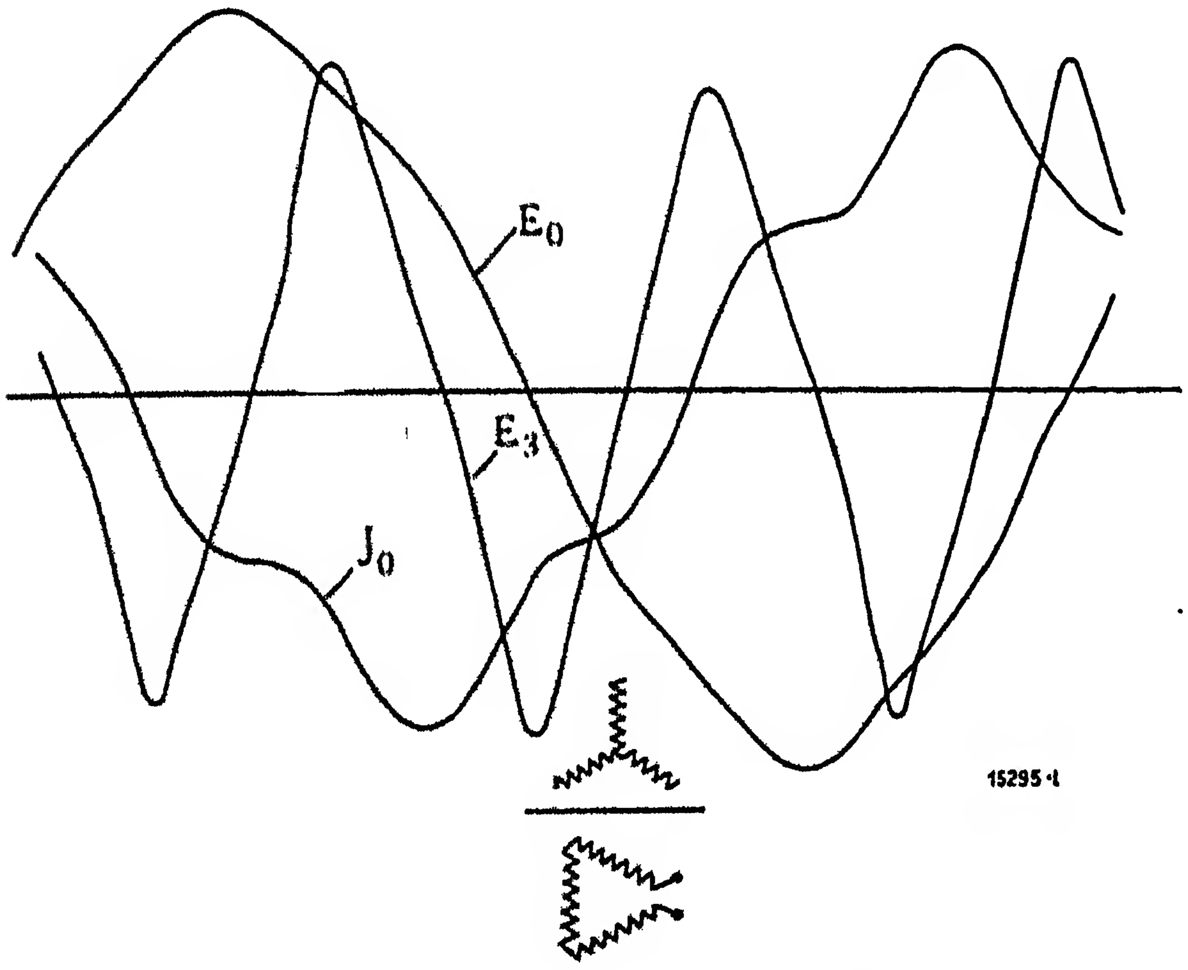


Fig. 17. Oscillogram taken from a 300-kVA, 433/1450-V, 50-cycle, star delta transformer with the flux density increased about 38%.
J_1 and E_0. Current and voltage on low-tension side.
E_3. Pressure on high-tension side with open delta.
E_0 600 V.
J_1 76 A.
E_3 1725 V.

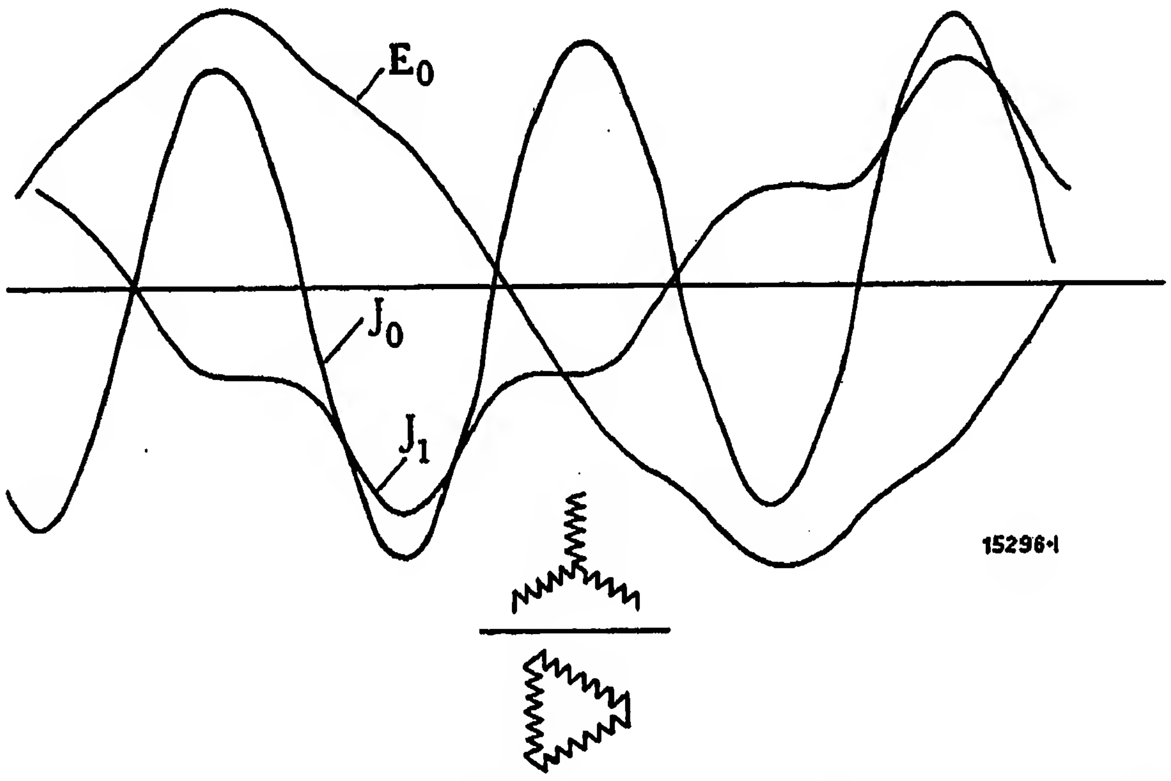


Fig. 18. — Oscillogram taken from a 300-kVA, 433/1450-V, 50-cycle, star/delta transformer with the flux density increased about 38%.
J_1 and E_0. Current and voltage on low-tension side.
J_0. Current on high-tension side with closed delta.
E_0 = 600 V
J_1 = 98 A.
J_0 = 4 A.

the waves in the three phases are an unbroken sequence. If, now, a third harmonic of pressure arises in the transformer, it causes a current to flow in the triangle but this current cannot flow out into the system to which the transformer is linked up, because the instantaneous value of this third harmonic is the same at all three apexes.

The behaviour of the iron core of a star-connected transformer towards the magnetic flux will be similar to that of a star-connected winding towards the current. The usual type of magnetic circuit for three phase transformers, which consists of three cores carrying windings, and two bare yokes, corresponds to the star method of connection. The formation of a third harmonic will, therefore, only be possible in a stray magnetic field between the upper and the lower yoke. It should be mentioned here that those iron parts which happen to come under the influence of this stray field may become the seat of undesirable losses. It is interesting to note that, although the magnetising current flowing through the winding of any one core under a purely sinusoidal pressure shows the presence of a third harmonic (Fig. 14), the magnetisation of a

magnetic circuit of the kind described corresponds to the fundamental pressure wave, the 5^{th}, 7^{th}, 11^{th}, 13^{th}, ... harmonics being left out of account. This is indicated clearly in Fig. 19, which gives the ampere-turns of two cores and shows that the deficiency in ampere-turns of one core is always made up for by those of the other. As the ampere-turns are not at the point where they are required, the stray field from yoke to yoke, already referred to, is produced, which field has a periodicity three times greater than the fundamental periodicity of the field. This stray field produces third harmonics in the phase pressure, which appear in the oscillogram Fig. 17 taken at the open delta apex. The pressure is measured at three times its phase value, because all three phases are in series.

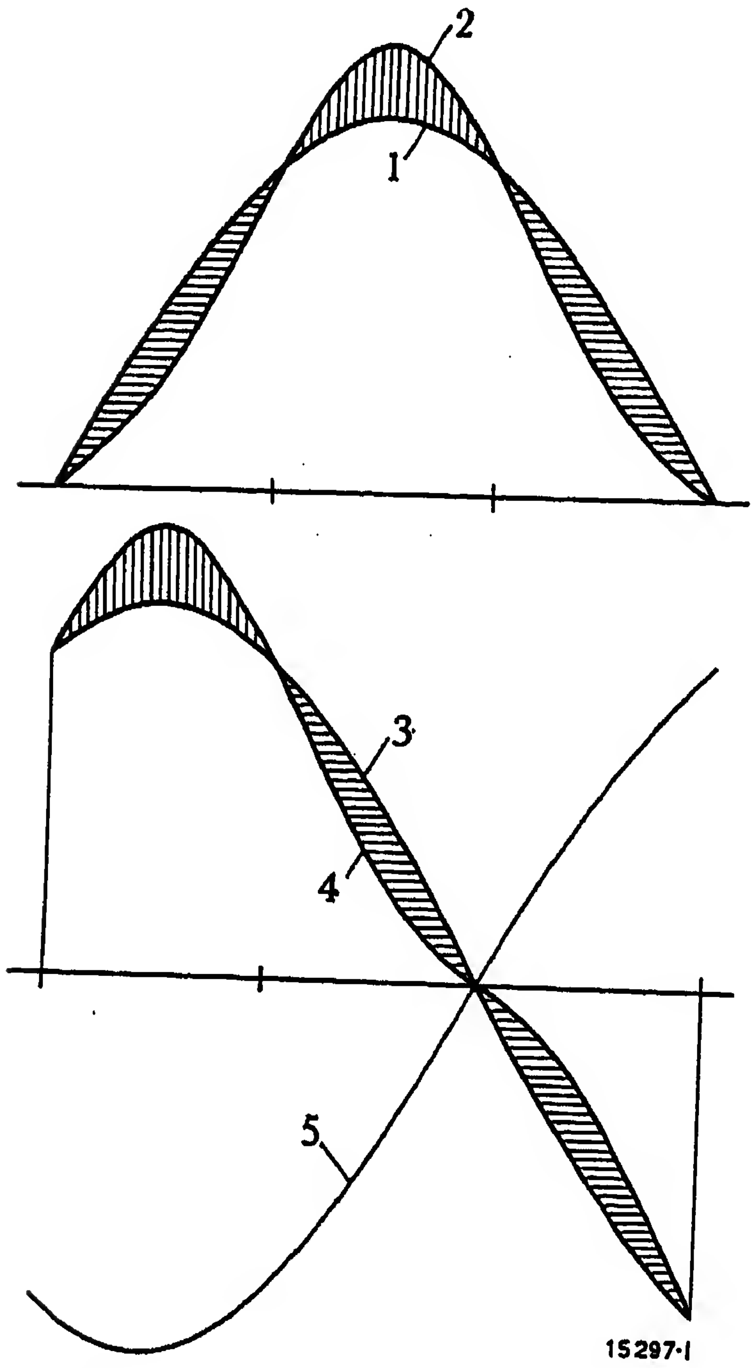


Fig. 19. — Curves of magneto-motive force (M. M. F.).

1. Existing M. M. F., outer core.
2. Necessary M. M. F., outer core.
3. Existing M. M. F., middle core.
4. Necessary M. M. F., middle core.
5. E. M. F. of middle core winding.

▤ Surplus M. M. F.
▥ Deficiency in M. M. F.

If the triangle is closed, as shown in Fig. 18, the current of the third harmonic shown flows in the triangle as a result of the pressure, and this current compensates for the deficiencies in magnetisation of the individual core windings, almost suppressing the stray field and practically keeping the third harmonic out of the phase pressure.

In three-phase transformers with the core as described, the cause of the third harmonic can only be traced to the stray field, and, therefore, its influence is obviously small. In three-phase banks formed of three single-phase transformers, the third harmonic has a somewhat stronger disturbing influence, because the above-mentioned compensation of the ampere-turns of each phase is no longer possible. If distortion of the phase pressure is to be avoided, it is at least necessary for one system of the main windings to be connected in delta, or else for a delta-connected auxiliary winding to be added to all three transformers. In either case, the third harmonic current will flow through the triangle equalising the magnetic fields in the 3 single-phase cores, in the manner described above.

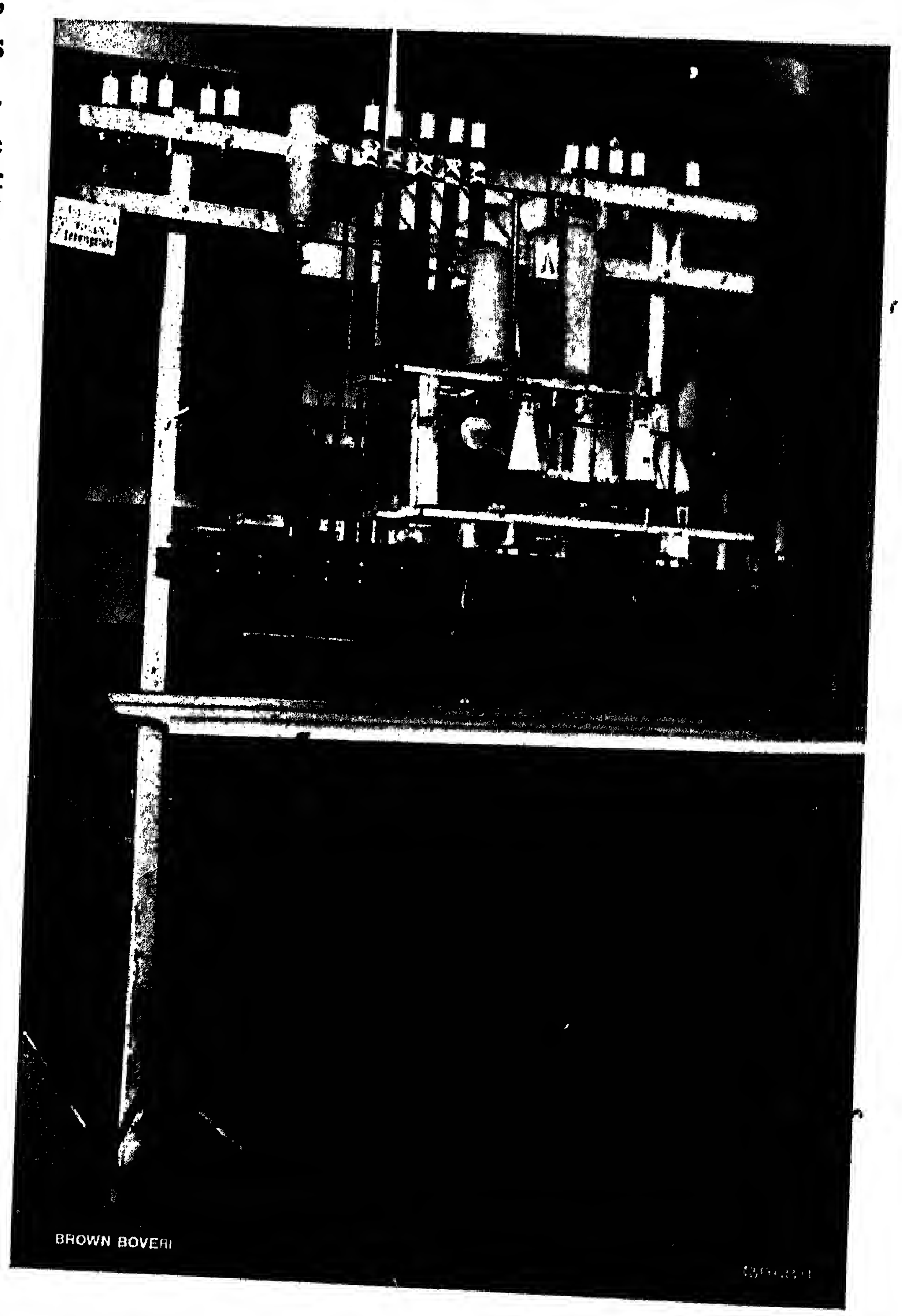


Fig. 20. — Arrangements for a surge test on a three-phase transformer, 6000 kVA, 57'000/8400 – 8200 – 8000 V, 50 cycles, star/star connection.

3. Strength of internal insulation. The latest tests made by Brown, Boveri & Co. on surge effects have confirmed the old principle, namely that coils must be thoroughly insulated from one another throughout. These tests have further shown the principles to follow in strengthening

the insulation. It is well known that switching operations, atmospheric disturbances, flashovers, and grounds on the system give rise to surges or travelling waves with steep fronts, and these put stresses on the transformer coils which, although of short duration, may attain a value equal to twice the normal pressure. It was, therefore, of value to discover by tests the order of magnitude of the stresses to which a coil might be subjected, in order to fix the strength of the wire and the coil insulation necessary.

With this object alone, a transformer of 6000 kVA was built, the special design of which allowed all kinds of tests to be carried out (Fig. 20). The large number of tappings provided on both sides, allowing of testing the different parts of the winding, are visible. Further, the figure shows the sphere-gap voltmeter, and further back, the excitation spark gap. On the top, the condensers of the oscillating circuit are seen, with their ribbed insulators. The numerous tests made with this transformer are described in the Bulletin des Schweizerischen Elektrotechnischen Vereins, 1922, No. 10, from which an idea can be formed of the thoroughness with which they were carried out.

The principal conclusion reached through the tests was that the stress put on the coils increased to different values from wire to wire and coil to coil, according to the distance of the earthing point from the transformer, that, however, all the stress curves lay within an envelope curve which was characteristic of the kind of coil insulation chosen. Fig. 21 shows curves of this kind together with the envelope referred to. The form of this curve is especially interesting. The stress increases to its maximum at the second coil, falls from the second to the fifth coil to a slightly lower value, which remains constant over several coils, falls slowly towards the end of the winding, and then increases again in the last coils up to about the value it had for the middle coils.

One can build up the insulation of the coils so as to suit this curve approximately, by strengthening the beginnings and ends of windings compared with the central part. It is also possible to insulate the whole winding in a manner corresponding to the highest stress on any coil. Tests showed that windings insulated evenly all through were subject to slightly, lower maximum stresses than the others. Brown, Boveri & Co. therefore favour the second method, but, if required, build transformers according to the first method, in which case the insulation of the central coils is always fully adequate.

In order to prove that transformers can stand up to high excess pressures, a pressure-surge test was added to the list of normal transformer tests. It is made with special transformer connections according to a Brown Boveri system, and is not only equivalent to those called for in the normal standard rules for the testing of transformers but takes more account of the conditions met with in practice. This test is carried through by subjecting the transformer to artificially created steep-fronted pressure waves of a prescribed height. To-day, a wave-front height of 1·3 times the normal pressure is used.

The progress made in reliable insulation for transformers naturally led to the idea of eliminating from the plant all protective devices such as choking coils, protective condensers and lightning arresters which, even to-day, are far from perfect, and the beneficial influence of which is doubtful, the transformer being built so that, combined with the earthing of the neutral over a choking coil or ohmic resistance, it can stand up to all excess pressures which occur.

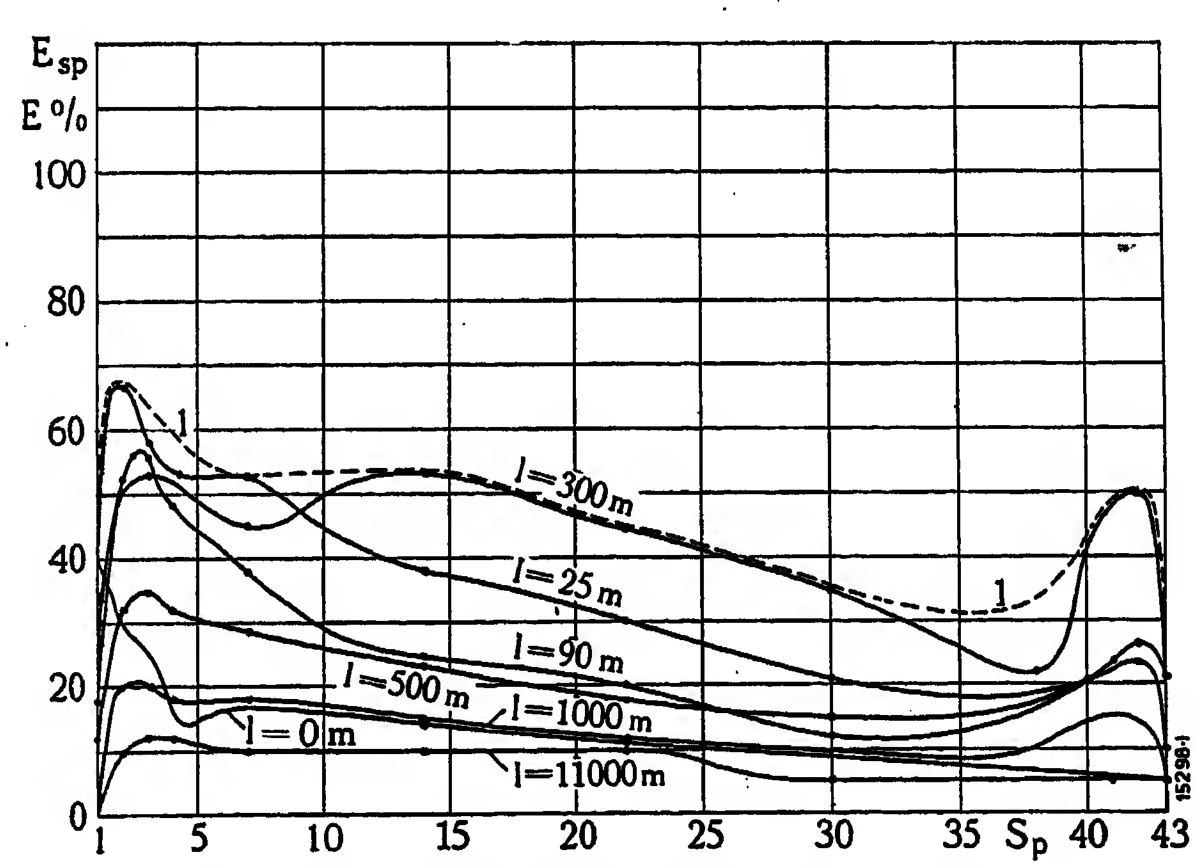


Fig. 21. — Distribution of the surge pressure throughout the coils of a transformer.

E. Amplitude of surge wave. **1. Envelope curve.**
Sp. Number of coils. **Esp. 10'000 V.**

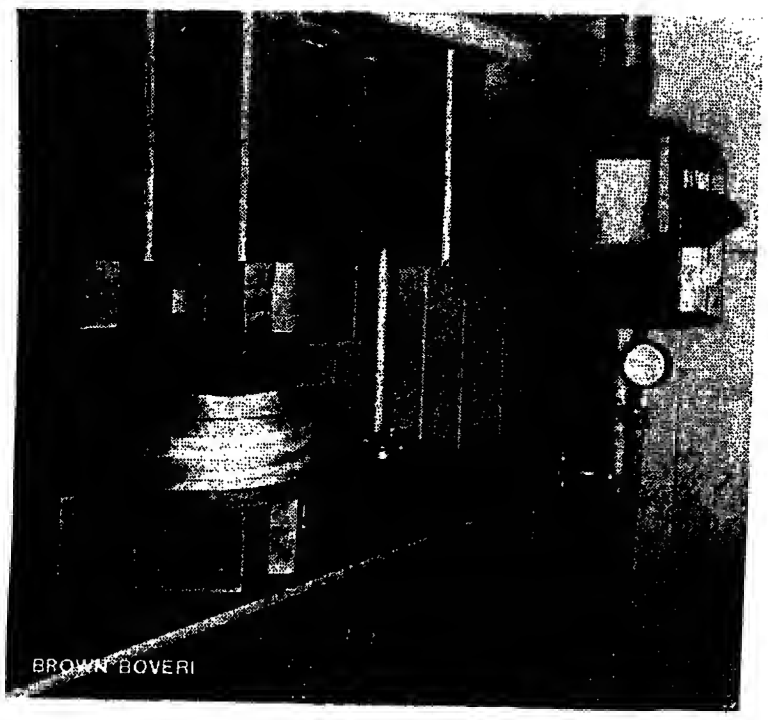


Fig. 22. — Compression test, with a 19-ton load, on an end distance ring for a 4000-kVA transformer.

This point of view has been held by Brown, Boveri & Co. for some time, and is continually gaining ground. It is obvious that it results in the simplest plants. In order, however, to remain in touch with practical experience, Brown, Boveri & Co. keep complete statistics of whatever faults occur, which allows them to judge of the real efficiency of the safety measures taken.

Apart from its protective value against surges, high-grade insulation has, the further advantage of protecting the edges of the conductor, the small radius of which cause a concentration of the lines of force. Fig. 23 gives a clear picture of the conditions, as it shows perfectly how the lines of force within the insulating sheath draw together to a density which is generally inadmissible for oil. The insulating material, however, will stand far higher stressing, and thus it protects those parts which are most subject to danger. It will be seen that the stress on the outside of the insulating sheath has already almost dropped to the normal value.

4. Strength of external insulation. The insulation of the high-tension winding from the low-tension winding has not undergone much modification. Brown, Boveri & Co. have been using for years, with most successful results, insulating cylinders of best material which practically exclude all possibility of a breakdown between the windings. Further, this security is much increased by using wire covered with very high-grade insulation.

Insulation from the iron core has undergone many changes. The most varied types of supports for the ends of the winding were devised and tested on special transformer models both electrically and, as shown in Fig. 22, mechanically.

The present transformer designs, therefore, incorporate the results of all these tests, and they have given most satisfactory proofs of reliability. An important factor in design is the protecting ring for windings. Figs. 24 a and 24 b show diagrammatically the distribution of stresses at the winding ends. Fig. 24 a represents conditions when a protecting ring is not used and Fig. 24 b conditions with a ring. The difference in the stressing, especially at the winding edges is very obvious. Further, it will be noted that, without a ring, nearly all the lines of force terminate on the low-tension winding, while, with a ring, a great number of these lines are attracted by the core. A special Brown Boveri method of calculation combined with graphics allows of estimating what particular transformer design is best suited to any given case and thus helps to avoid mistakes.

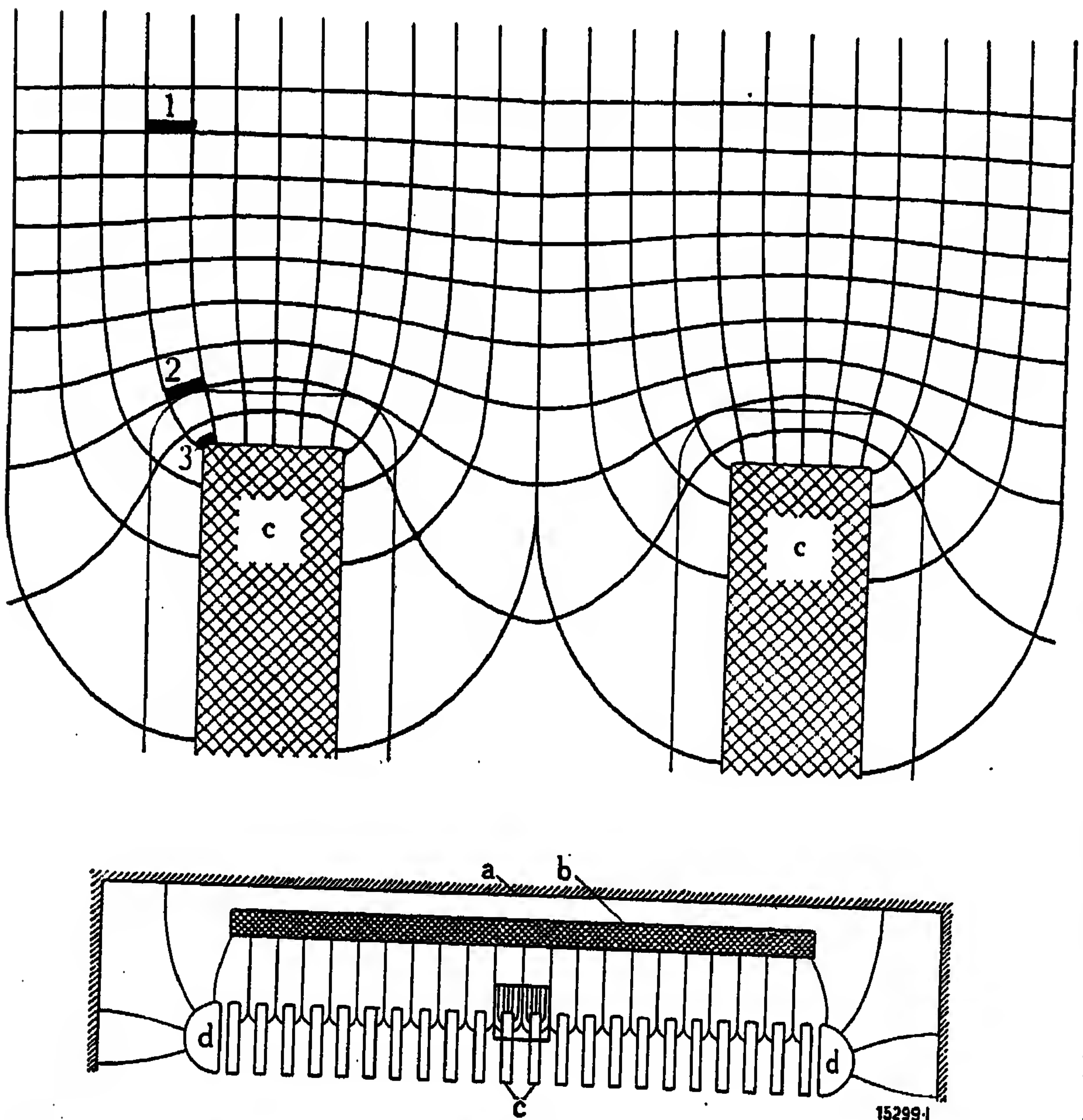


Fig. 23. — Distribution of the electric field in high-tension coils provided with oil slits.

1. Normal stress in oil.
2. 1·1 times normal stress.
3. 3·4 times normal stress.

a. Iron.
b. Low-tension coil.
c. High-tension coil.
d. Protective ring.

Once it had been proved that the careful insulation of the coils was a very important factor it was clear that strong insulation had to be used on all conductors within the transformer, and further, that all parts subject to particular stressing had to be specially carefully insulated. Thus, in insulating connections to the neutral point and

the tappings, the problem of determining the highest stress to which these parts will be subjected, is gone into very thoroughly. The great care exercised in manufacture is justified by the value of large transformers and is indicated by the successes obtained in practice.

5. Heating and additional losses. While on the subject of the advantages pertaining to good insulation of the conductors, its inherent disadvantage must not be forgotten, namely, the greater difficulty in heat dissipation. The knowledge gained through years of practice in dealing with

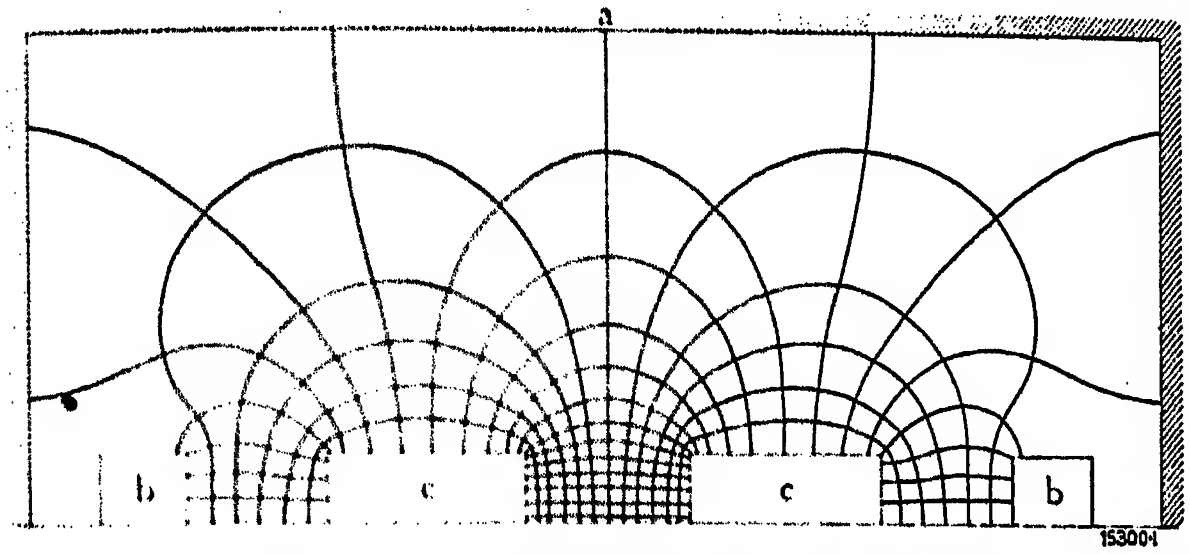


Fig. 24 a. Distribution of the electric field at the winding ends without protective rings.

a. Iron. b. Low tension. c. High tension.

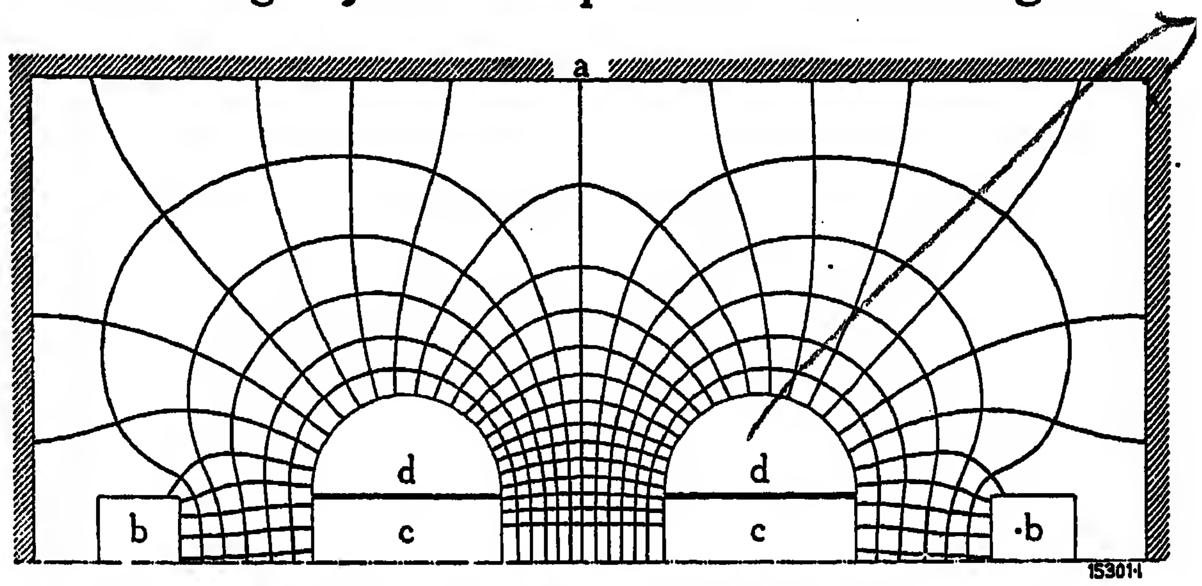


Fig. 24 b. — Distribution of the electric field at the winding ends with protective rings.

a. Iron. b. Low tension. c. High tension. d. Protective ring.

heat problems was of use here, but had to be extended to meet the conditions resulting from heavy insulation. Above all, methods of calculation had to be checked by many practical tests and modified when necessary. We would refer here to Fig. 7 and also to what was said on pp. 9 - 10. The consideration of this question showed the necessity of handling the problem of heating along with that of additional copper losses. Thus, the tests, on low-tension windings especially, led to the more frequent use of coils with oil slits between them. This type of winding has the advantage of presenting good cooling conditions, and of being very resistant to short circuits, over and above the advantage it has of giving good insulation. It is thus much used despite its expensiveness because Brown, Boveri & Co. have made it a principal to put reliability before any question of cost.

The study of the additional losses shows the importance of keeping the latter as low as possible, because they not only cause bigger total losses and temperature rises but produce unequal heating of the individual conductor layers, thus endangering the insulation at certain points. Fig. 25 gives a picture of the distribution of additional losses and of the temperature rise of the copper compared with the oil, in a coil composed of several layers. As, however, any increase in the width of the wire a, which acts as cooling surface, causes a big increase in the additional copper losses, there remains no other solution to the designer than to subdivide the conductor, that is to say, to place several wires in parallel, which, of course, makes winding considerably more expensive. By a clever arrangement of the conductors and special winding design, Brown, Boveri & Co. have been able to suppress the additional losses practically completely. Only in special cases, when the construction offers special difficulties, when the winding is made easier and stronger by less subdivision, and also when the cooling surface gives the necessary heat dissipation, some additional losses, which are calculated beforehand, are allowed.

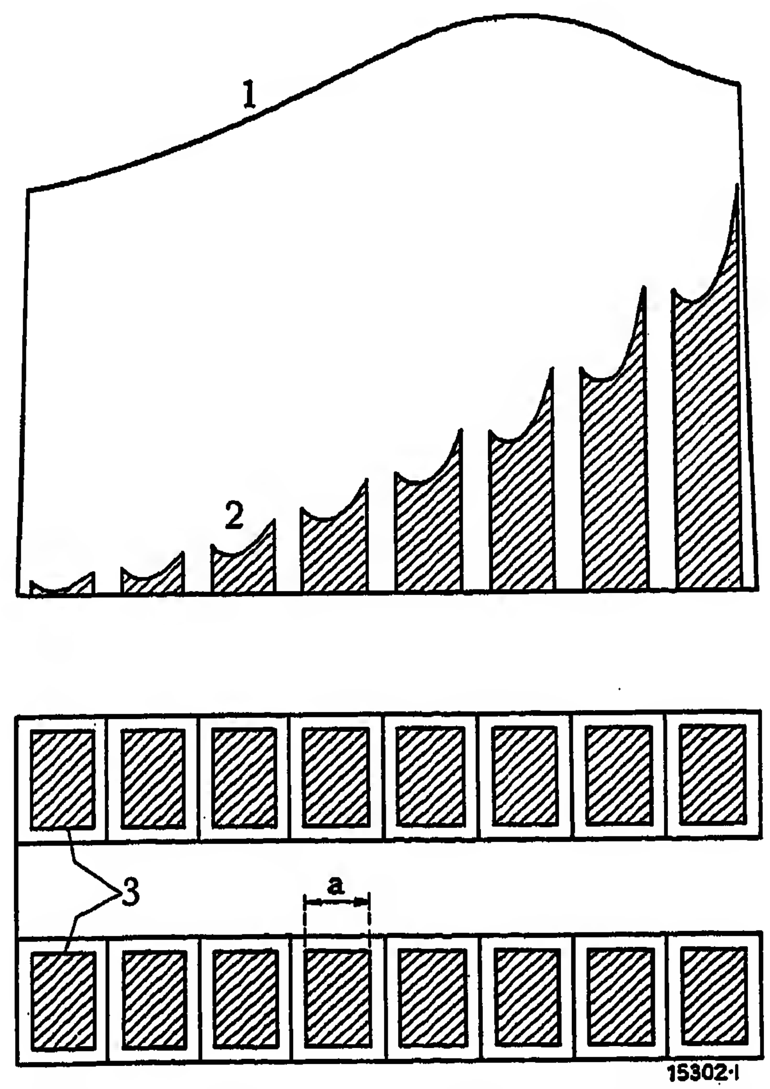


Fig. 25. — Distribution of additional copper losses and temperature in a coil with cooling slits.

1. Temperature distribution.
2. Additional losses in each separate conductor.
3. Coil.

6. Impregnation. In order to examine thoroughly all insulating materials used, Brown, Boveri & Co. have their own laboratories in which these materials undergo mechanical, physical, and cheminal examination. Too much caution cannot be exercised in the utilisation of new insulating substances. In this connection, we would mention much vaunted processes of impregnating insulating materials with all kinds of preparations and varnishes, which processes are widely advertised but seldom come up to expectations. In principle, the use of impregnated insulation is quite justified, as the process renders the material immune from acids which may appear as a result of oil decomposition, prevents the penetration of damp, and thus increases and maintains the strength of the insulating material. The more obvious their qualities seem, the more care must be exercised in testing to see that they really exist. It will often be found that one insulating material will not stand up to the temperature test while another is susceptible to the changes undergone by the transformer oil; many others, again, are deficient in insulating qualities or mechanical regidity. After years of patient research, and thanks to the work of the chemists and physicists in their own laboratories, Brown, Boveri & Co. succeded in perfecting an impregnating substance possessing all the necessary properties. Since that period, Brown, Boveri & Co. have adopted the process of impregnation.

7. Types of winding. Of the three well-known types of transformer winding, the Sandwich type, in which high and low-tension coils succeed one another down the length of the core, is the only practical one for pressures up to 20'000 volts. Double concentric windings are suitable for large outputs with pressures up to about 65'000 V with small short-circuit pressures.

If a high short-circuit pressure is called for, or if the transformer is designed for still higher tensions, the simple concentric winding is the best.

The demand for high short-circuit pressures in large plants, is generally recognised to-day as being justified, because it makes for a small short-circuit output; in other words, it reduces the stresses imposed both on machines and on oil switches when a short circuit occurs. With simple concentric windings attention has to be concentrated on the no-load current, which can easily attain a most undesirable figure, owing to the length of the cores. If, however, the section and induction be chosen judiciously, this current can be kept within admissible limits.

In transformers for big outputs, it is necessary for the forces which come into play during a short circuit to be estimated, and for the windings to be calculated from the point of view of mechanical strength. As already mentioned, these calculations demonstrate that, thanks to their form, the resistance to deformation of concentric windings during a short circuit is very considerable, and that, by heavy anchoring devices, which often include springs, they can be made absolutely proof against the forces exerted during short circuits.

The question of tappings on big units is related to that of the windings, and here we would recall the great danger which badly placed tappings may be to a transformer.

The switching of coils in and out of the winding means a rearrangement of the ampere-turns, and this means that the balance of primary and secondary ampere-turns, attained for normal conditions by careful calculation, is destroyed. Any lack of symmetry may lead to quite considerable axial forces causing deformations and contacts between coils, and thus endangering the whole transformer. The method by which these dangers are avoided, in cases where tappings are necessary, has already been mentioned on page 10.

IV. COOLING.

The heat generated in the iron core and in the copper must not only be transmitted from these to the oil, but from the latter to the cooling agent (air, water, etc.). The oil fulfills a twofold purpose, firstly as a first-class insulating substance, secondly as a heat transmitter. The high factor of utilisation of material attained in modern transformers makes special designs to give efficient cooling to the active parts of big units essential. Previous paragraphs describe these designs. There are three principal methods of eliminating the heat contained in the oil.

1. Natural cooling. By this method, the heat contained in the oil is transmitted to the surrounding air. Owing to poor heat radiation from the sides of the transformer tank, a considerable surface is necessary. In transformers for large outputs with relatively heavy losses, and quantities of heat produced commensurate with these losses, ordinary corrugated sheet-metal sides for the tanks are not sufficient. Brown, Boveri & Co. build the tanks for these big units with exceptionally deep corrugations, or with pockets of corrugated sheeting added, to increase the surface of radiation. This design suffices for units up to about 2000 kVA output (Fig. 26). For bigger outputs, radiators are added. These are composed either of a large number of tubes, or of special receptacles of corrugated metal which are connected to the main tank at top and bottom by means of tubes. These devices are designed and built so as to be absolutely oil-tight. Fig. 11 shows a transformer with radiators, which has an output of 15'000 kVA at a frequency of 50 cycles. The construction of a unit for this output with cooling by natural means is a feat worthy of note, and one which was only made possible by the experience of years and scientific design. The demand for transformers for large outputs with natural cooling tends to increase, because, when compared with units having artificial cooling, they can be said to require practically no supervision in service. Natural cooling is very suitable for outdoor transformers.

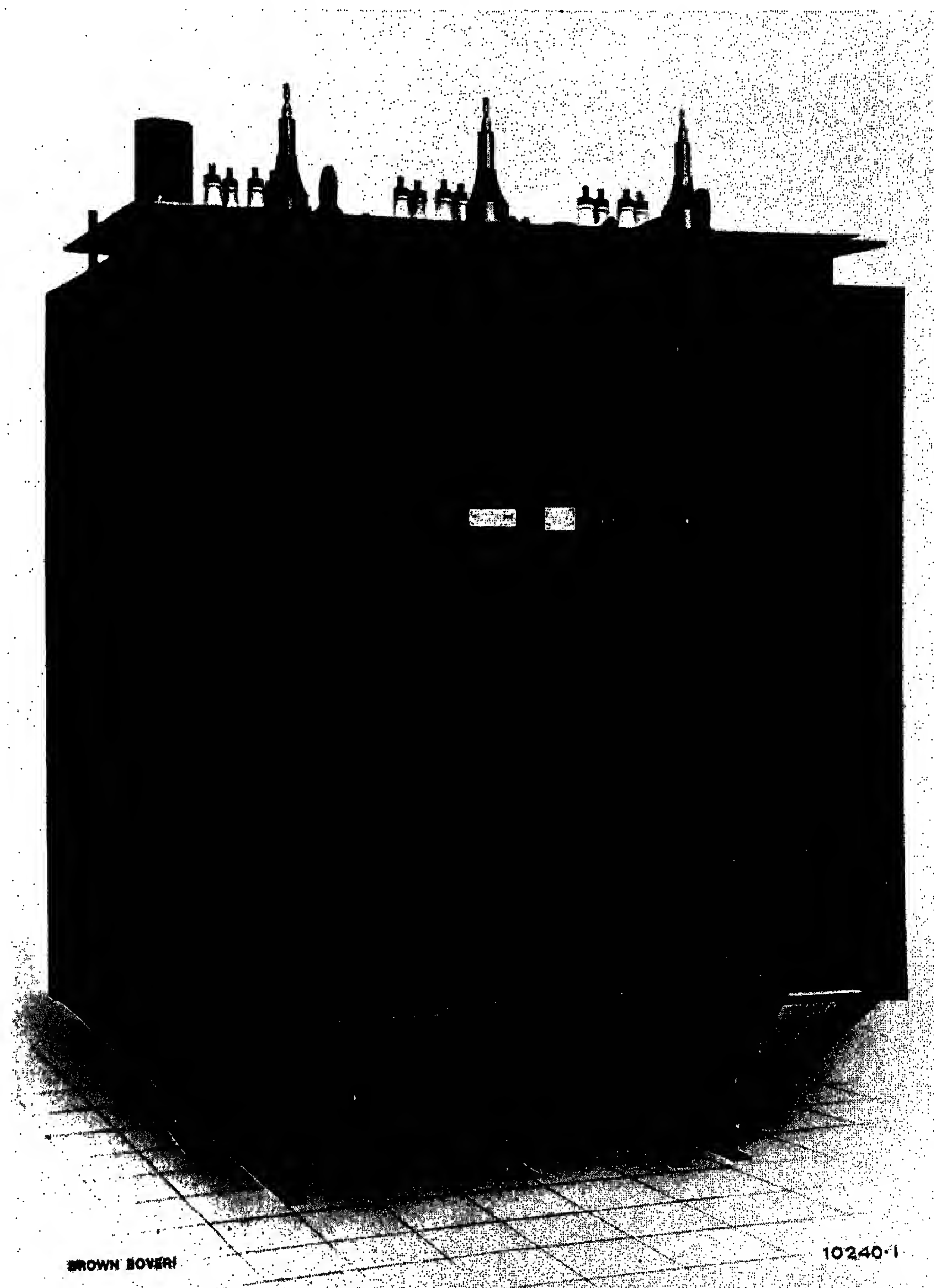


Fig. 26. — Transformer with natural cooling, 3000 kVA, 50'000/10'865—10'625—10'337—10'048 V, 35·1/166 A, 50 cycles, star/star connected, oil-tight design with oil conservator (removed) and safety valve.

2. Internal water cooling. Transformers cooled in this manner are built with coils of ribbed piping

situated inside the upper part of the tank. Cooling water circulates through these coils, which are so dimensioned that 0·9 litres of water per minute are sufficient to dissipate one kilowatt of transformer losses. Special attention is given to the flanged connections of the piping, to make it absolutely water tight. Fig. 27 shows a transformer of this type built for 6000 kVA, 52'500/10'000 V, 50 cycles.

It is of great importance that the oil should be able to circulate freely, especially in units with natural cooling or with internal water cooling, because in these transformers the only force which makes the oil flow is its difference in density at different points in the tank. The oil, cooled by contact with the inside walls of the tank, sinks while the oil circulating in the slits and ducts of the core and windings is heated by the latter and rises. Brown Boveri transformers for large outputs are carefully designed with the object of allowing as free a circulation of the oil as possible. This assures efficient cooling of the active parts, so that there can be no overheating.

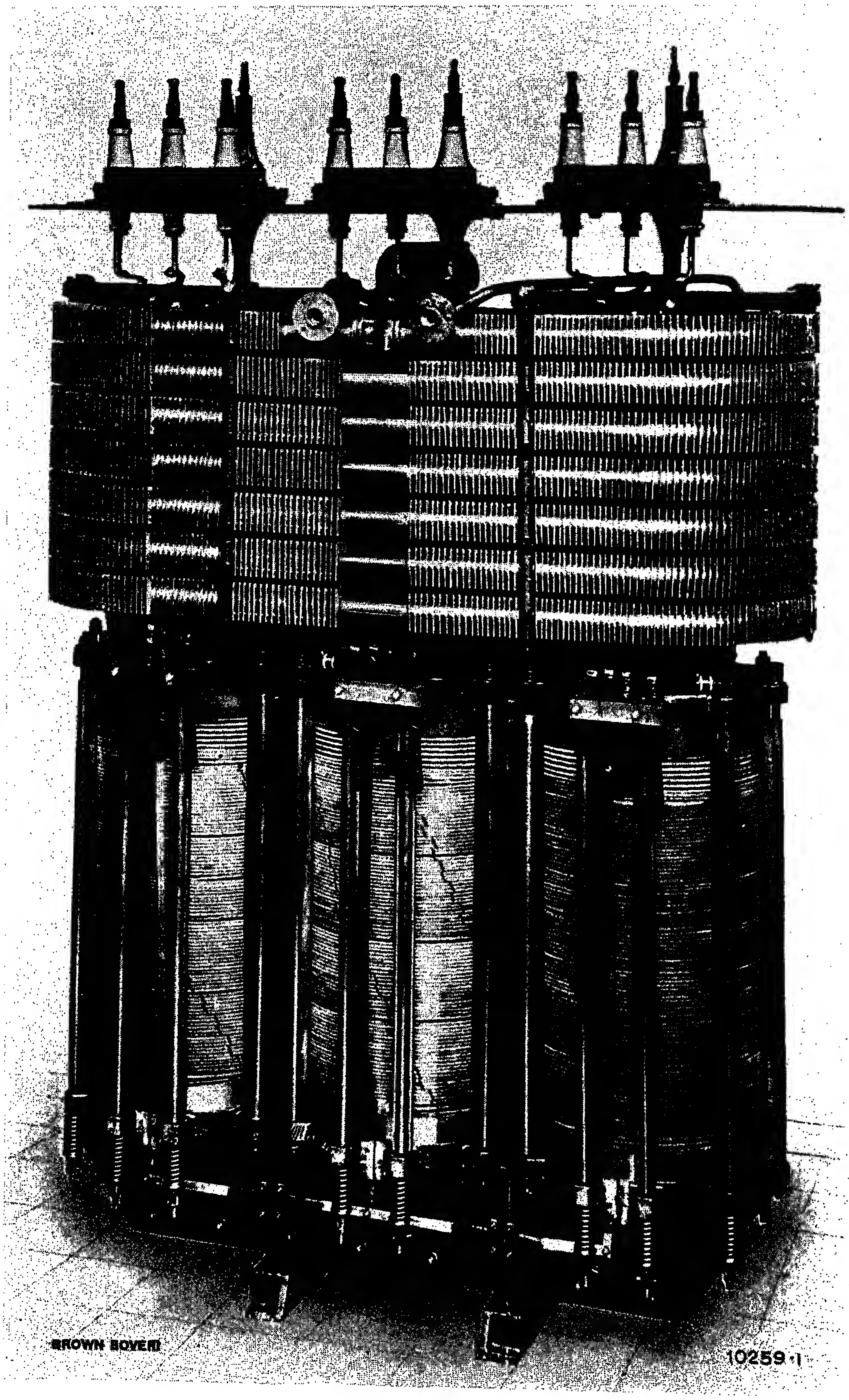


Fig. 27. — Three-phase transformer with internal water cooling, 6000 kVA, 52'500/10'000 V, 50 cycles, star/star connected.

3. External oil circulation. With this method of cooling, the hot oil in the upper part of the tank is drawn off by a pump and sent through a cooler, whence it is injected into the lower part of the tank again. In this way, the lower part of the tank is under a considerable oil pressure and the oil can be said to be forced into the slits and ducts of winding and core. Very strong oil circulation is thus assured and, with it, specially intensive cooling of all the active parts of the transformer.

Centrifugal oil pumps are generally chosen, toothed-wheel pumps being more seldom used: special attention is given by Brown, Boveri & Co. to the glands, which must be made much tighter with hot oil than is the case with water. The oil pump is driven by an ordinary D. C. or A. C. motor, the latter being generally a four-pole type when the current supply is at a frequency of 50 cycles. With single-phase current at lower frequencies, commutator motors are employed. The output of the oil-pump motor is from one

to six kilowatts according to the size of the transformer. Pump and motor are direct coupled and mounted on a common bedplate. The quantity of oil in circulation amounts to about six litres per min. for every kilowatt of losses. The head created by the pump depends upon the conditions on site. For normal lay-outs (pump placed at the foot of the transformer tank) the manometric head of the pump is not quite one atmosphere. Fig. 28 shows the lay-out of a 13'000-kVA transformer and its cooling plant.

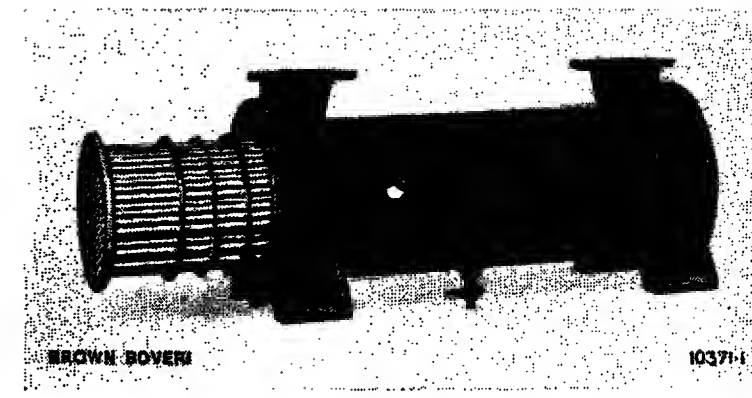


Fig. 29. — Brown Boveri oil cooler with water chamber removed and cooling tubes partly taken out.

The oil is cooled either by water or air, and Brown, Boveri & Co. build coolers of both kinds suited to the requirements of the plant. Fig. 29 shows a Brown Boveri cooler for water. The principle parts of this cooler are a cylindrical chamber with two cast-iron end covers. This chamber contains a nest of cooling tubes of a special brass alloy held in position by end plates of special bronze. The cooling water flows through the tubes, while the oil is guided by special rings along the inner wall of the chamber. Care is taken to make the tube joints perfectly tight and to provide for the expansion of the tubes under the influence of heat. Long practical experience has shown that the cooler should be erected in a vertical position, as thus impurities drop to the bottom, and the lower water chamber can be removed to be cleaned by simply loosening some bolts

Fig. 28. Three-phase transformer with external cooling set, 13'000 kVA, 8600—7835/84'300 V, 50 cycles.

For transformers of medium or large outputs, two coolers are used in which the oil circulates in parallel while the water circulation of the two coolers is in series. The utilisation of two coolers has the advantage of allowing one of them to be cleaned while the other remains in service. Under these conditions, the transformer can continue to deliver 80—100 % of its normal load for about 1 hour, which time is generally sufficient to finish the cleaning operations.

Despite much investigation, the problem of corrosion in oil coolers has never been quite cleared up, as is proved by the latest technical articles published. It has, however, been shown that impurities in the water, or its acid or alkaline nature, as well as the tubes employed (character of the alloy, crystalline structure, and internal tensions) are

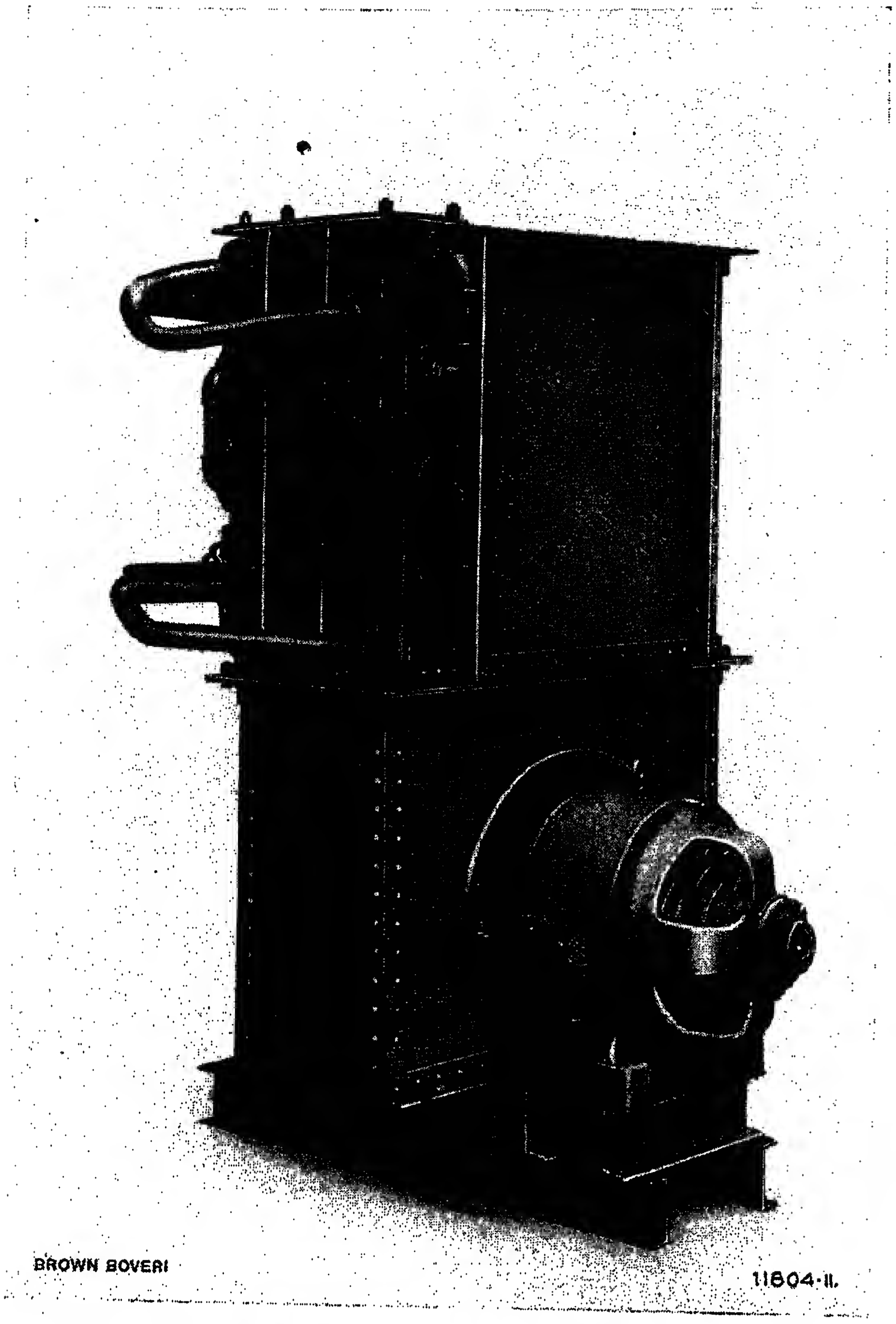


Fig. 30. — Oil-cooling set. Cooling is effected by a stream of air. Cooler capacity 40'000 calories per hour.

the chief factors in corrosion. Brown Boveri & Co. use best grade homogeneous materials in the construction of their coolers, which years of service show to be impervious to corrosion, and further, they have at their disposal laboratories so equipped that the suitability of materials to each particular case may be readily tested.

The *amount of cooling water* used per kilowatt of transformer losses is about 1 litre per minute, allowing for a temperature of 15° C. at the water inlet. The pressure at the water inlet should be about 0·4 at. (gauge) and the water must be free to flow off unhindered at the outlet. For this reason, the regulating cock must always be put on the inlet side. In this way, the pressure of the oil in the cooler is always greater than that of the cooling water, so that, if leakage occurs, there is no danger of water percolating into the oil piping and thus reaching the transformer.

Fig. 30 shows a Brown Boveri oil cooler with air cooling. The fan set and the cooler form a single unit. The cooling capacity of this cooler is about 50 kW. This type of cooler is in growing demand for transformers on electric locomotives and for plants where little cooling water can be obtained.

V. PROTECTIVE APPARATUS AND ACCESSORIES.

Absolute reliability with transformers of large outputs can only be attained by constant supervision, because in service certain factors have to be reckoned with over which the manufacturer of the transformer has no control. Among others, we would mention overloading and stoppages in the supply of cooling water. For this reason, Brown, Boveri & Co. have attached particular importance to the development of reliable control and alarm apparatus intended for transformers of large outputs, such as dial thermometers, remote temperature-indicating devices, alarms actuated by a stoppage in the flow of cooling water or cooling air, and oil-flow indicators. These are all designed to be connected to a signalling device.

The dial thermometer is a combination of the mercury thermometer and the manometer. This apparatus can either be built on to the transformer itself, or the indicating instrument, connected to the thermometer by capillary tubes, can be fitted on to the transformer tank or on to an adjacent desk panel. This instrument indicates on a scale the temperature of the upper layer of oil in the tank to within an accuracy of about 1° C. It is provided with a contact device which closes the circuit of an alarm bell if a given temperature be reached. Thus, notice is immediately given of excessive temperatures in the transformer.

For measuring the temperature from considerable distances, resistance elements with a high temperature coefficient are employed. These can be linked up to either a D. C. or an A. C. circuit, suitable instruments being used as indicators in combination with auxiliary resistances connected

in the form of a Wheatstone bridge. The instruments in question are specially calibrated and fitted with a suitable temperature scale. When the resistance elements are fed by alternating current they can be built into the transformer winding, a current transformer being inserted in the system to separate the measuring and main circuits. This process is hardly possible with high tensions, and therefore, in transformers for large outputs, resistance elements are placed in the vicinity of the winding so as to measure the temperature of the oil flowing directly from the windings. It is true that this method does not give the actual temperature of the winding copper, but exhaustive researches in the Brown Boveri laboratories have shown that the error is small and always constant, and can, therefore, easily be taken into account. Further, when the load fluctuates, the temperature change of the oil lags very little behind that of the windings. This arrangement of the resistance elements has the advantage of allowing them to be easily removed by simply unscrewing, while, with the resistance elements built into the windings, the whole winding must be dismantled before the elements can be removed for inspection or replacement. Generally another resistance element is lodged in the tank in the upper layer of oil. By means of the remote temperature-indicating device the engineer can regulate the temperature conditions of the transformers from the control room.

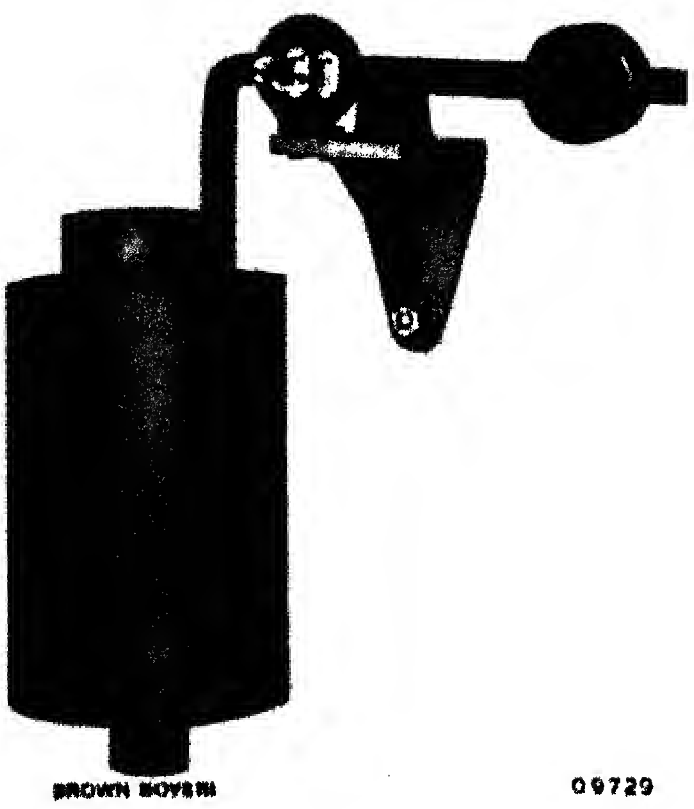


Fig. 31. — Water-circulation alarm device for indicating cessation of water flow in water-cooled transformers.

Transformers built with forced cooling are provided with a device which indicates any stoppage in the flow of the cooling fluid. Fig. 31 shows a device of this kind for water-cooled transformers. It is provided with a contact arrangement connected to the alarm circuit. Indicators of the same kind are also built for coolers with air cooling.

For transformers with external oil circulation *oil-flow meters* are incorporated in the oil piping (Fig. 32). These allow of ascertaining the quantity of oil flowing and carry a contact device which closes an alarm circuit if this quantity falls below a certain figure.

For the alarm circuit, either D. C. or A. C. can be used. The actual alarm apparatus takes the form of either an acoustic or an optical signal. Fig. 33 shows diagrammatically a complete signal layout for a large transformer with water cooling. In this case, the control board is distant 150 meters from the transformer station proper. The installation does away with the necessity for constant special supervision, because the ordinary station operators can do all that is required, with the help of the remote temperature indicator and signalling devices.

Fig. 32. — Brown Boveri oil-flow meter.

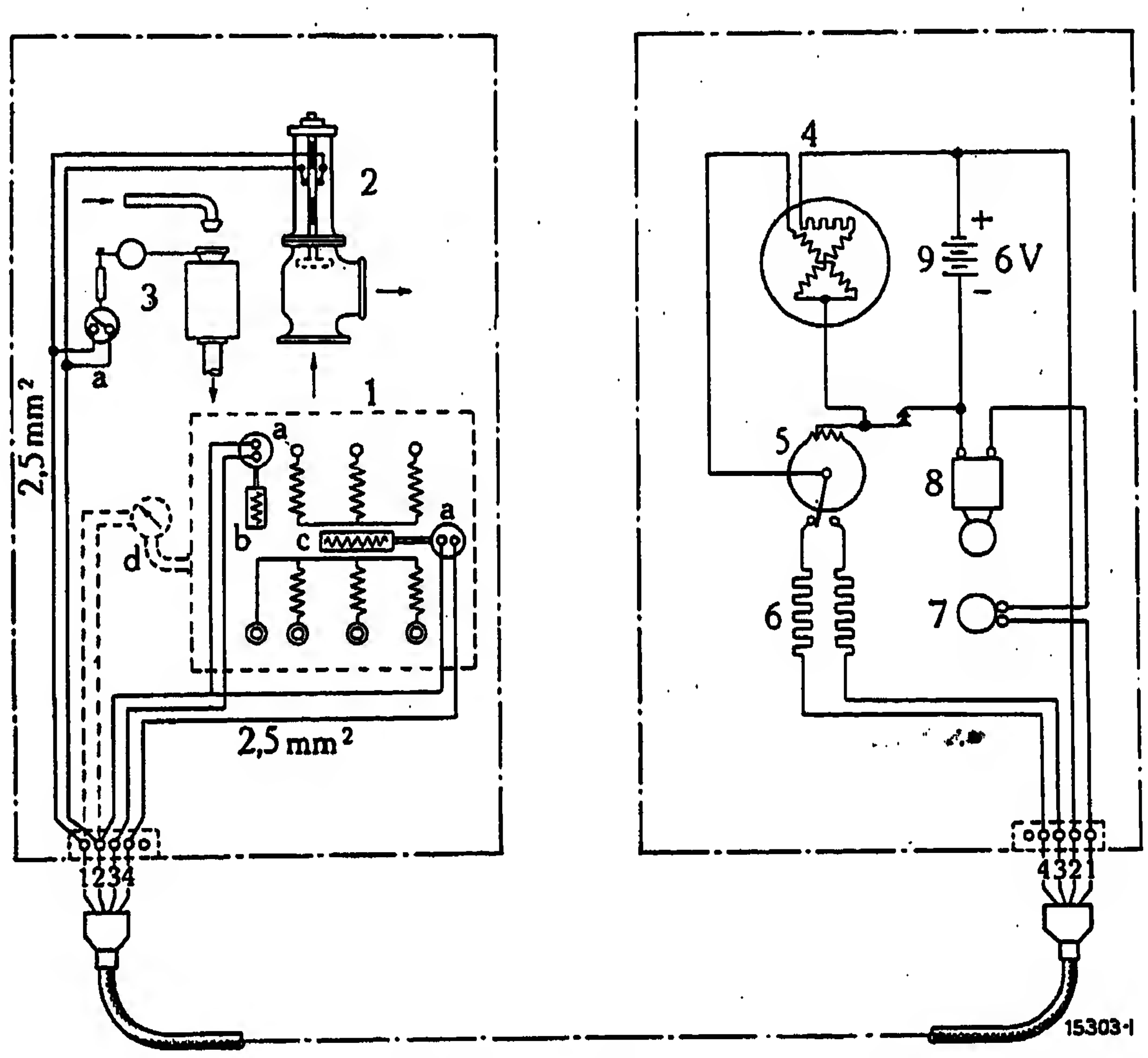


Fig. 33. — Signalling device for a transformer with external water cooling.

1. Transformer.
1a. Resistance element.
1b. Point where measurement is taken in oil.
1c. Point where measurement is taken in windings.
1d. Contact thermometer.
2. Oil-flow meter with minimum-flow contact.
3. Water-circulation signalling device.
3a. Contact.
4. Temperature indicator.
5. Change-over switch.
6. Compensating resistance.
7. Switch contact on shaft of oil switch of generator, in position "in".
8. Alarm bell.
9. Battery.

VI. THE OIL FILLING.

The use of high-grade transformer oil only is one of the most important factors in assuring reliability in service and in prolonging the life of the transformer. To-day, mineral oils alone are used. The qualities essential to make them suitable for transformers are: high flash point, high ignition point, high specific gravity, low viscosity, and low setting or clouding point. The behaviour of the oil under the influence of heat, that is at high temperatures in the vicinity of copper and exposed to air, and the effect of the oil on the insulating materials are important points. Many years ago, Brown, Boveri & Co. recognised the importance that should be attached to the quality of the oil filling, and they developed special processes to test the suitability of oil for use in transformers. The physical properties enumerated above can be determined by the usual methods, while the setting point is ascertained by the so called flow-curve method which is the only one giving exact results. We would mention here an article in the Brown Boveri Review 1922, No. 1, describing this method, in detail. An exceptionally low setting point is not essential for transformers in general, exept for outdoor units which may lie idle for long periods at very low temperatures. Under these conditions, the oil may harden in the radiator tubes or oil circulating system, and thus form an obstacle to the circulation. With the transformer oil now used by Brown, Boveri & Co. this is no longer possible, as this oil has a setting point of from —28 to —31° C.

The principal quality required in transformer oil is that it should be capable of withstanding the effects of heat. Even with transformers provided with oil conservators, the oil is in contact with air which tends to oxidise it. Further, the catalytic action of the copper must be reckoned with. Both actions tend to form deposits which settle on the coils and core as well as in the cooling apparatus. As a result, heat dissipation is diminished, and the temperature rises, which, in its turn, increases the sludging of the oil. This goes on until the excess temperature causes an accident. For this reason, about 20 years ago, Brown, Boveri & Co. developed a process for testing oil under conditions closely resembling those occurring in practice. The effect of temperature on oil under the influence of air and in the presence of copper was thus ascertained (Fig. 34). Tests carried out quite lately show that the usual tar-content test as used in Germany and the "Sludge" method used in England give no adequate idea of the extent to which the oil can withstand heat. The Brown Boveri method was, therefore, still further developed as described in an article on this subject in the Brown Boveri Review 1922, No. 8. These improved methods, which alone take into account all practical requirements, will probably be more generally adopted in future. Together with the tests for determining deposit formations under the influence of high temperatures, the influence of oil on cotton tissues and paper have been tested. After heating these insulating substances for a long period in oil, it was shown that their strength was diminished. This gives a standard for estimating the suitability of a given oil, as one of its qualities should be to affect insulating material as little as possible.

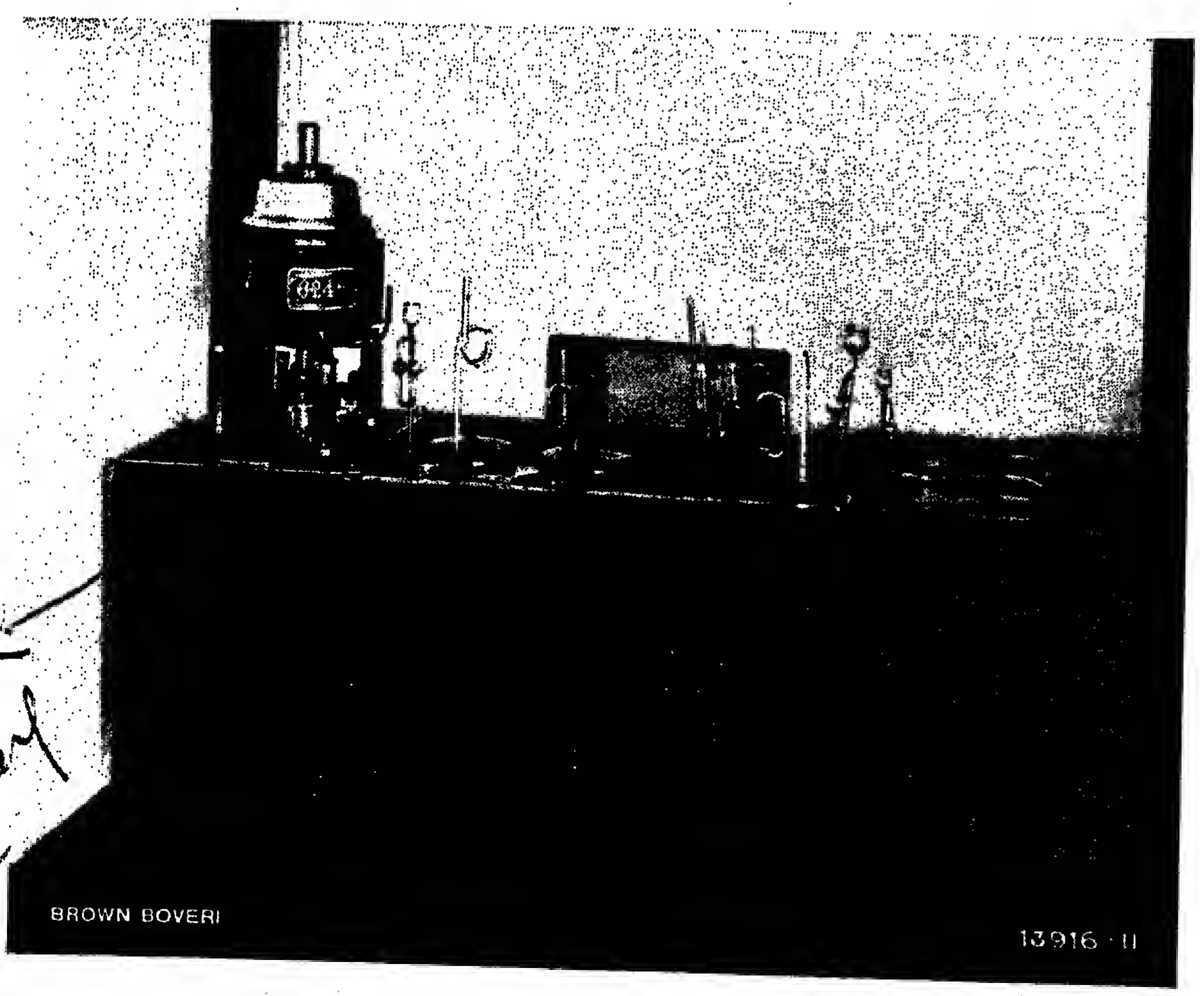


Fig. 34. — Brown Boveri oil-testing apparatus for testing transformer oil.

To make the description of these tests complete, a word must be said on the subject of the breakdown pressure test. This is more a proof of the purity of the oil than of its insulating quality. As is known, the breakdown pressure for oils can be increased to 80'000—100'000 V between spheres of 12.5 mm diam. with a

5-mm gap, by means of careful filtering. The presence of the slightest impurity, however, such as dust particles etc. which are generally hygroscopic and take up any humidity present in the oil, causes bridges to form in the electrical field and quickly effects a reduction in the breakdown pressure. Practically it is impossible to free an oil filling entirely from dust, so that the breakdown test is really of secondary value in showing the suitability of a given oil for transformer use.

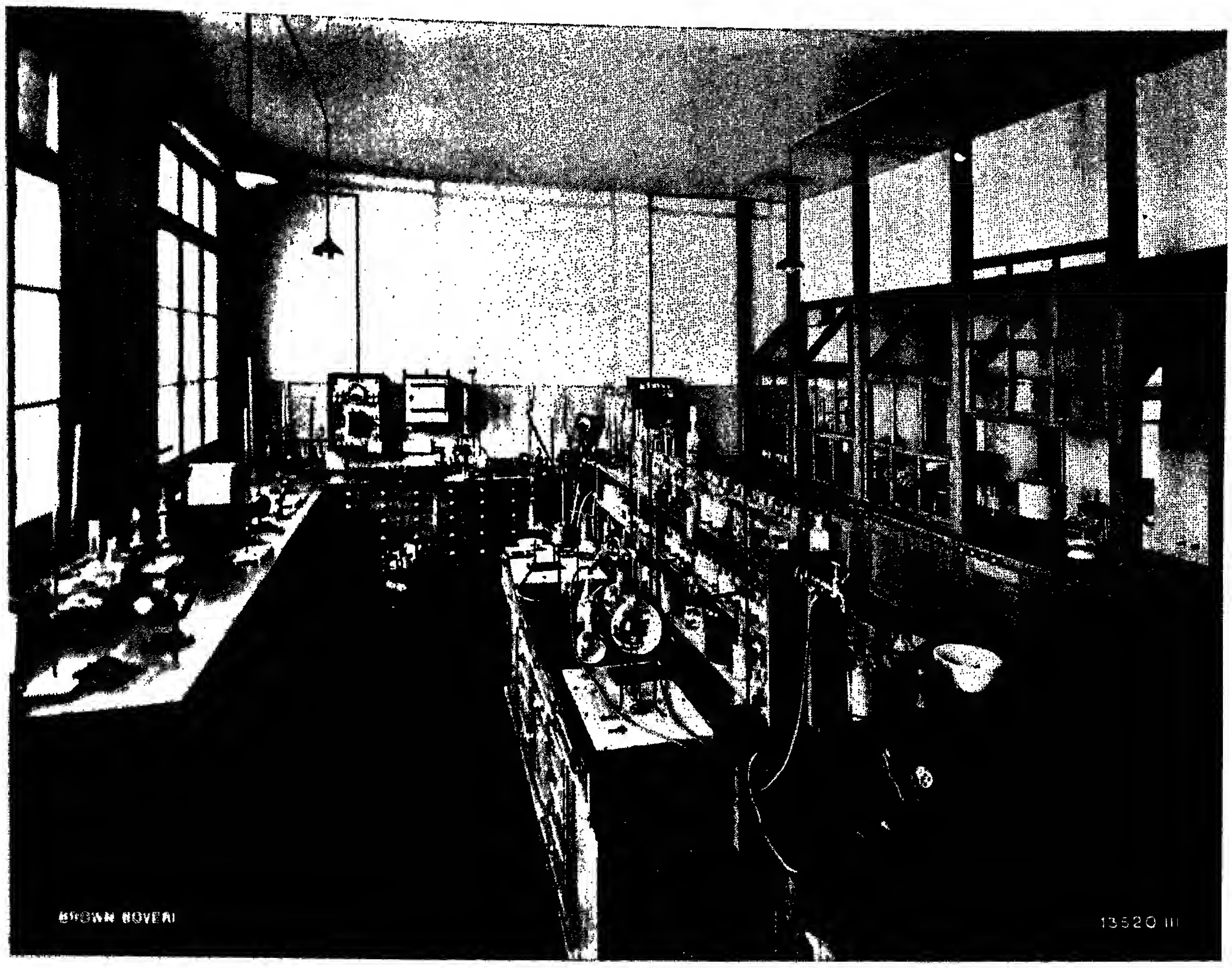


Fig. 35. — The Brown Boveri chemical laboratory—organic section.

The above mentioned testing methods, and their splendidly equipped chemical and physical laboratories, put Brown, Boveri & Co. in a position to obtain for their transformers the most suitable oil on the market. All samples of oil delivered at the works are carefully tested in every way before a choice is made. Samples are then taken from the oil chosen when delivered in quantity, and these again are carefully tested. Thus, only first class oil corresponding to the samples first delivered are used for filling the transformers. The research work of Brown, Boveri & Co. has so influenced the firms delivering oil to them that, to-day, transformer oil is obtained, which, after being heated for 300 hours at 112° C. in copper vessels to which air has access, shows no deposit whatever. Thus the transformer oil now delivered is again equal to pre-war quality, which, as far as can be judged, showed only a

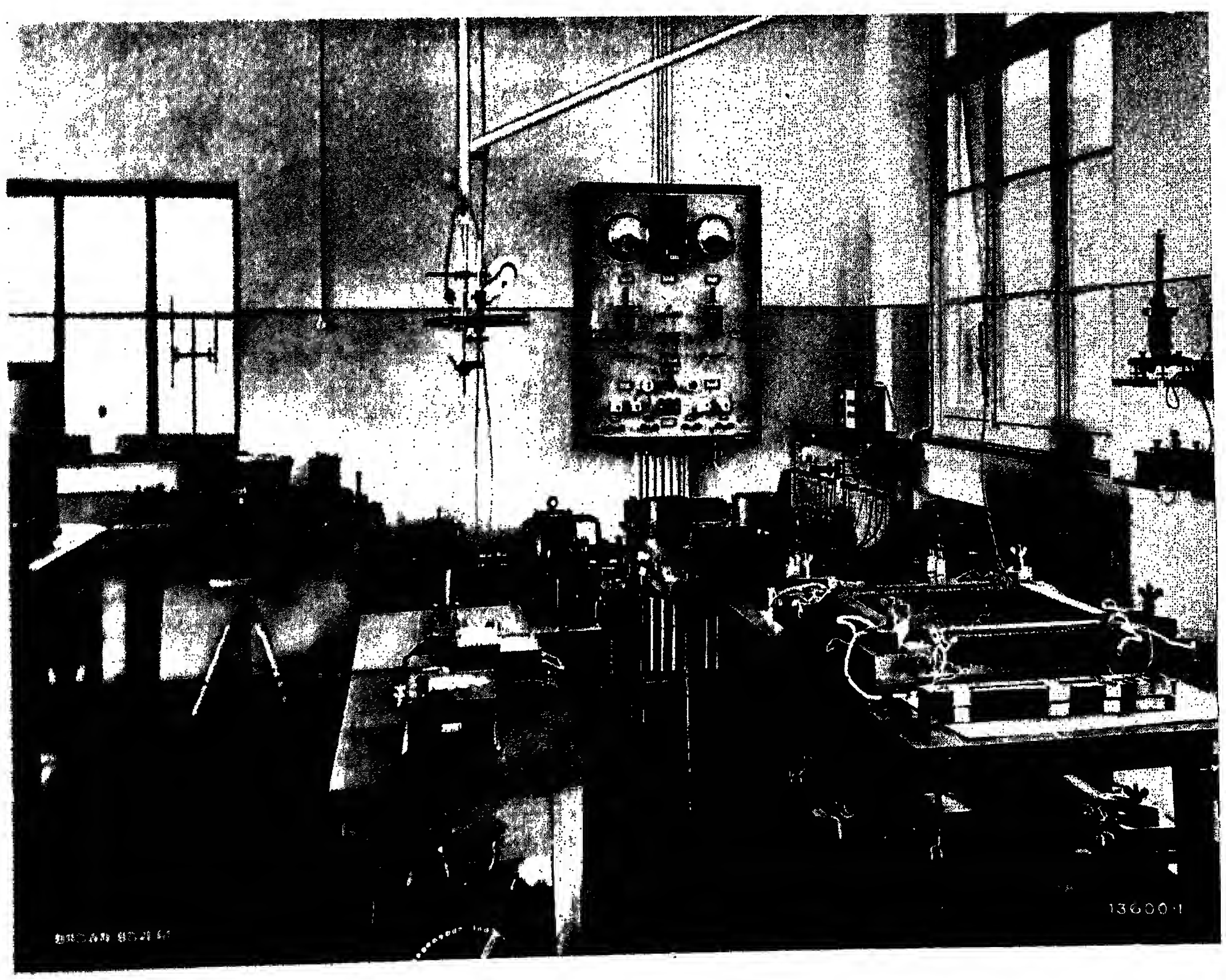


Fig. 36. — Test room for transformer laminations.

Fig. 37. — Double excentric press in stamping room for producing transformer stampings.

slight discoloration after years of service. This is an advantage which cannot be too highly appreciated from the point of view of the reliability and length of life of the transformer.

VII. THE BUILDING OF TRANSFORMERS FOR LARGE OUTPUTS.

The manner in which a design is carried out is of as much importance to the success of the finished product as the design itself. From the first, Brown, Boveri & Co. devoted themselves to problems of practical construction and are in a position to guarantee the quality of their products, thanks to the thorough tests to which the raw material used is subjected, to special processes of manufacture and construction, and also to perfectly equipped testing department and laboratories, which are also used for making any special tests of interest.

The following is an account of the processes involved in the manufacture of transformers for large outputs:

1. Core. Samples are taken from the sheeting delivered at the works for the manufacture of the core stampings, and these samples are tested with regard to both their magnetic and mechanical properties. Fig. 36 is a view of the room in which these tests are carried out. The sheeting is only released for use if the tests have shown that the material is suitable for the purpose for which it is required. It is thus possible to make certain that the iron losses correspond to the figures calculated and guaranteed beforehand, and also to avoid disagreeable surprises, such as the losses of the finished transformer exceeding those allowed by the specification to which it was built.

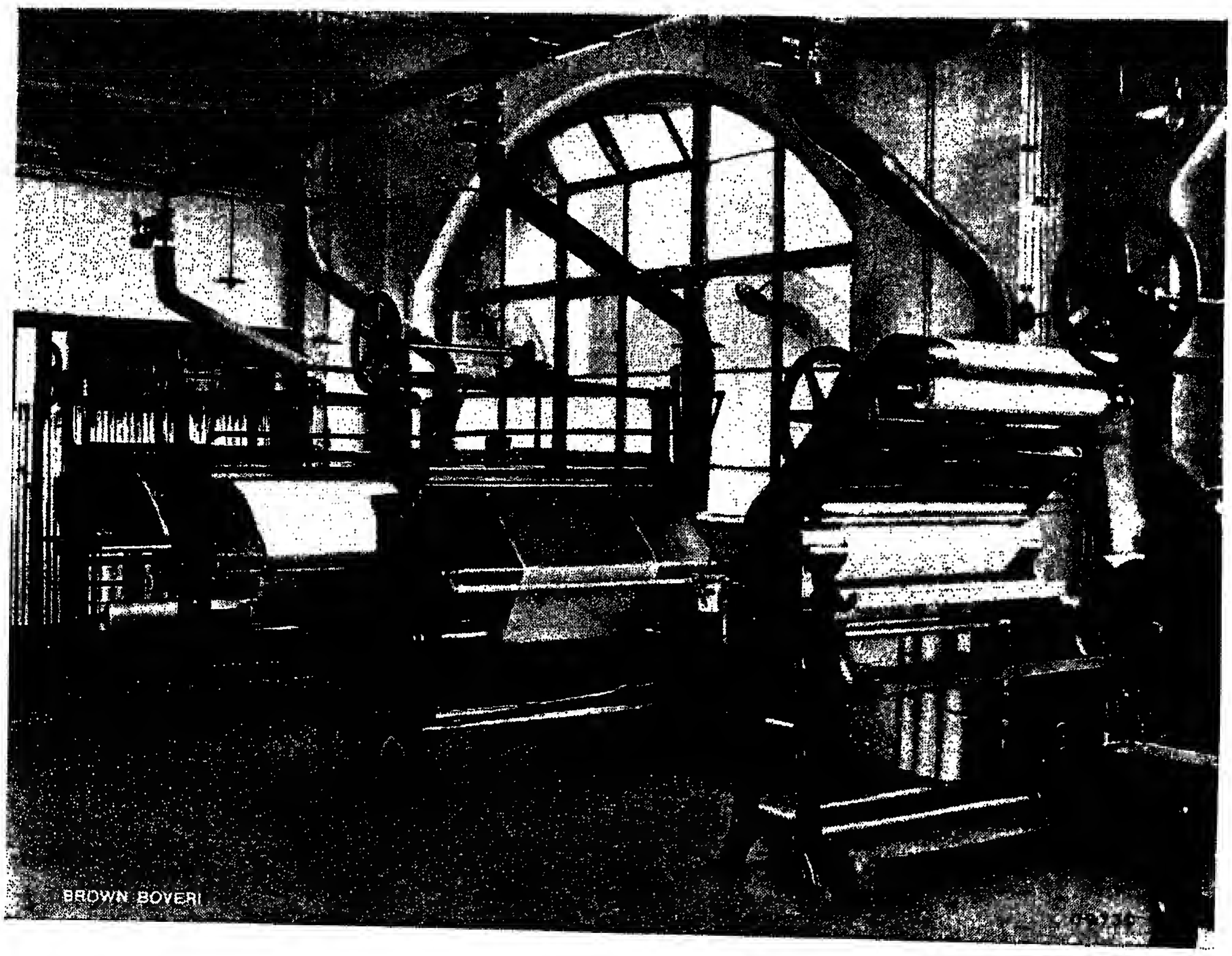


Fig. 38. — Machines for making insulating tubes.

When certified as up to standard, the sheeting is passed through a special machine which pastes a sheet of insulating paper over one side. The sheets are then either put into stock or passed on directly to the stamping shop (Fig. 37), where they are stamped out in suitable

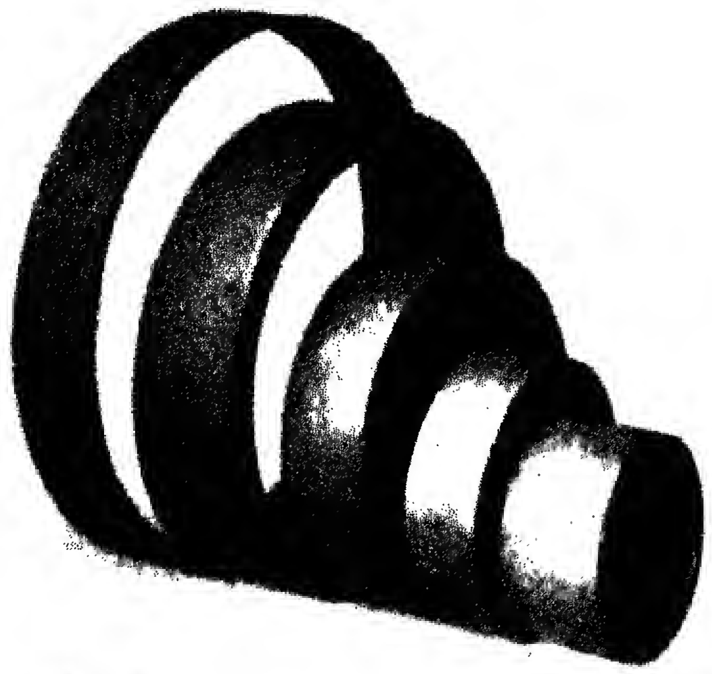


Fig. 39. End distance rings of Bituba.

forms. These stampings are then loosely assembled to form cores and yokes and compressed under the action of powerful hydraulic presses. While still under the press, the clamping bolts are fitted, after which the surfaces which are to butt together are machined on special planing machines. The results of this process have proved entirely satisfactory.

2. *Coils.* The copper delivered is also tested as to quality and dimensions before being insulated and placed on the winding machines where the coils are formed. These are pressed, dried out in special drying ovens, and impregnated. Thus, coils and windings are produced which are extremely compact and mechanically rigid. The high degree of perfection attained in the manufacture of single coils and windings for transformers is shown in Fig. 43.

3. *Insulating parts.* A special section of the works is devoted to the manufacture of insulating parts, such as tubes, distance rings and distance pieces of Bituba, and insulators of Bituba or Bakdura. Fig. 38 shows a part of the shops for manufacturing insulating tubes and Fig. 39 shows some finished Bituba distance rings. The raw material as well as the finished articles are here subjected to the severest tests, as in the cases previously referred to. These tests are carried

Fig. 40. Erecting hall for large transformers.

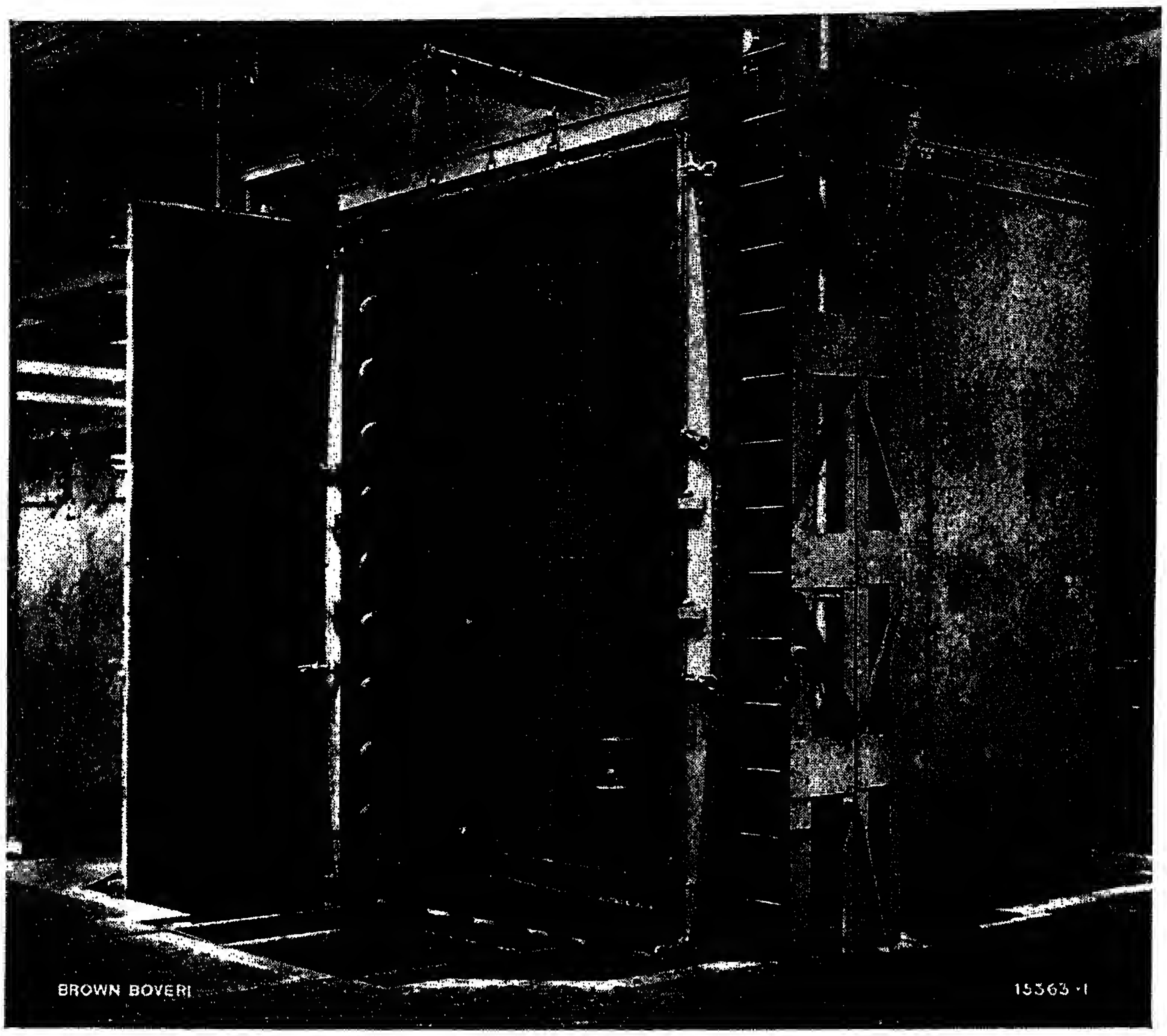


Fig. 41. — Vacuum chamber for drying out completed transformers.

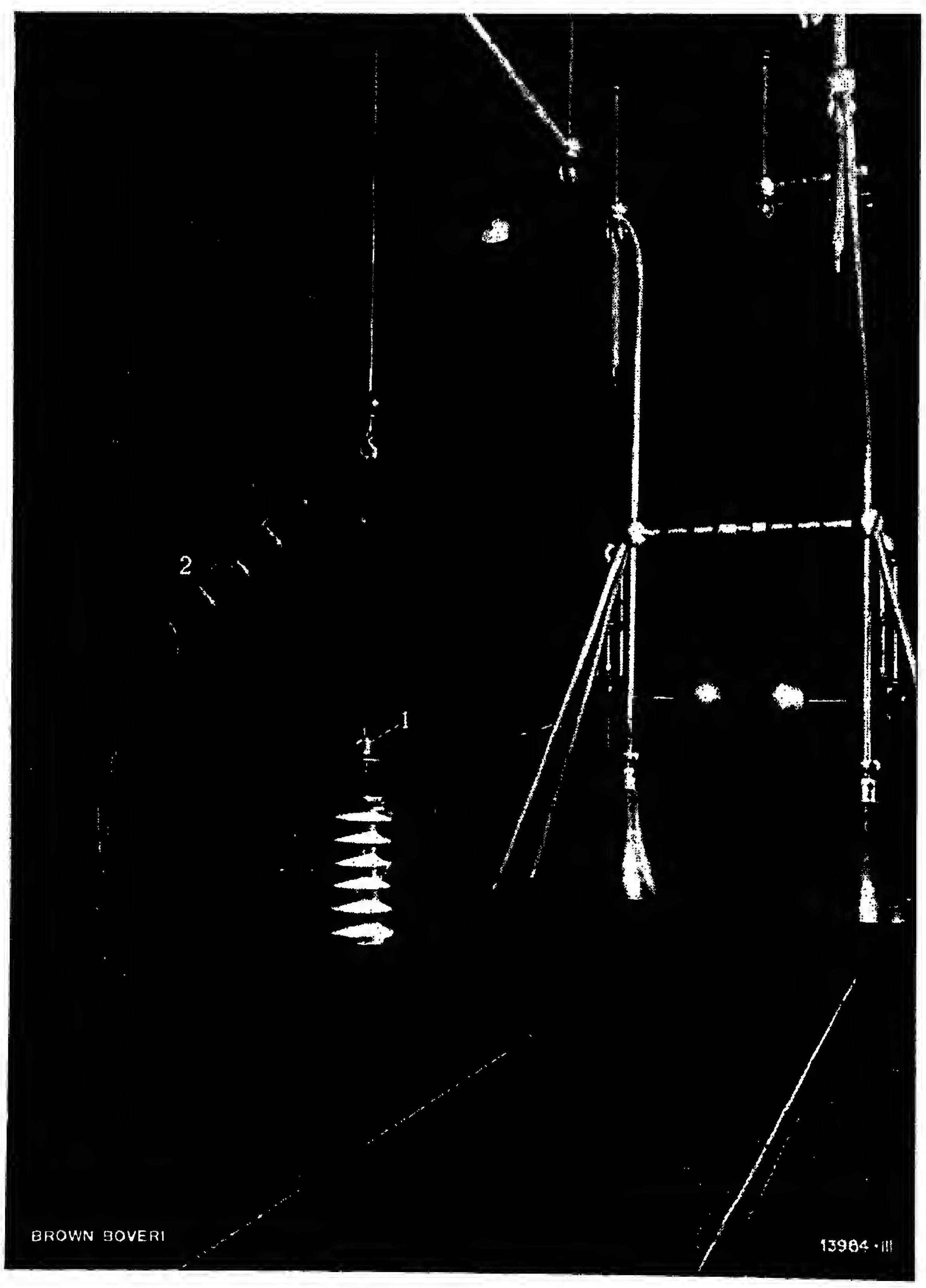


Fig. 42. — High-tension room in transformer testing department. Pressure test on a 110'000-V bushing under rain conditions.

out on the raw material in chemical and physical laboratories, while the finished products are tested in a special high-tension test room attached to the transformer workshops.

4. Tanks. The transformer tanks are built either in Brown, Boveri & Co's own branch works in Munchenstein, or, under the supervision of engineers of the firm, in the boiler shops of certain Swiss manufacturers. Before being taken over, all tanks are tested as to oil-tightness.

5. Erection. The manufacture of the separate parts, mentioned above, is carried out in the different shops simultaneously and according to a programe fixed in advance for each particular order. In this way, quick delivery can be effected. It is possible to have the different separate parts delivered on the same day to the erecting shops, where work can be begun on them without loss of time. Fig. 40 gives a view of the new erecting hall for large transformers. This hall is equipped with every modern appliance for speedy and careful transformer erection. The top yoke is first lifted from the finished iron core and the windings placed in position. The upper yoke is then fastened in position again, the insulators are secured, and the leads and connections between the coils are added and insulated. The transformer is now ready for a first test, that is, for a test of the number of winding turns and of the connections. If the active part proves to be in order, it is placed in the tank and the latter is filled with oil.

6. Drying out. After the above work has been completed, the transformer is dried out in vacuo. The care given to this operation is a factor of great importance as regards the life and reliability of the unit. The drying process is, therefore, the object of the greatest attention and takes place under constant supervision. According to their size, the transformers are left from five to eight days in the vacuum tank

(Fig. 41) where they are subjected to a temperature of 85—100° C. under a vacuum of 94—99%. In this way, air and moisture are completely extracted from the transformer.

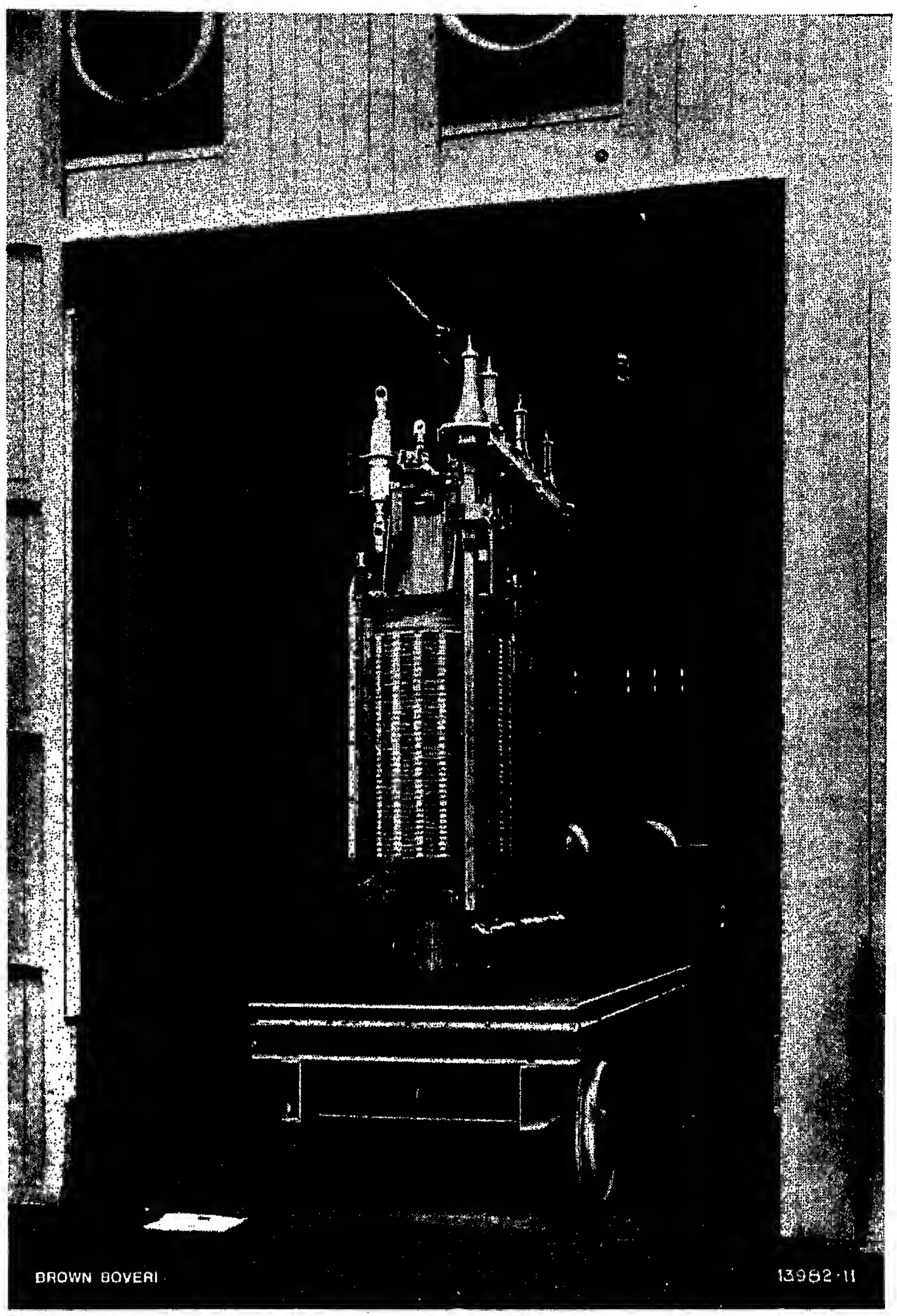


Fig. 43. — **High-tension room in transformer testing department. Transformer being wheeled in for testing.**

7. *Final tests.* Upon the conclusion of the drying operation, the transformer is subjected to a final inspection and testing. It is lifted out of the tank and the bolts, supports etc. are tested once again, after which it is passed on to the test room. This is adjacent to the erecting hall and was built at the same time as the latter. A detailed description of the whole of the new transformer testing installation is given in the Brown Boveri Review, 1923, Nos. 6 and 7. The tests to which the finished transformer is now put are the following:

1. Measurement of pressure ratio.
2. Measurement of no-load losses.
3. Measurement of short-circuit pressure and of copper losses with the transformer short-circuited, to check the current distribution in the windings and to determine the efficiency and pressure drop.
4. Measurement of the ohmic resistances of windings.
5. Insulation test between windings and core.
6. Insulation test of the turns of the winding, to make which the transformer is supplied with current at double normal pressure and double frequency, and, for very large units, with 1·3 times normal pressure at normal frequency.
7. Surge test. This test, introduced some years ago, allows of testing the insulation of coils and turns under a pressure many times higher than normal.
8. Heating test, especially for new designs.

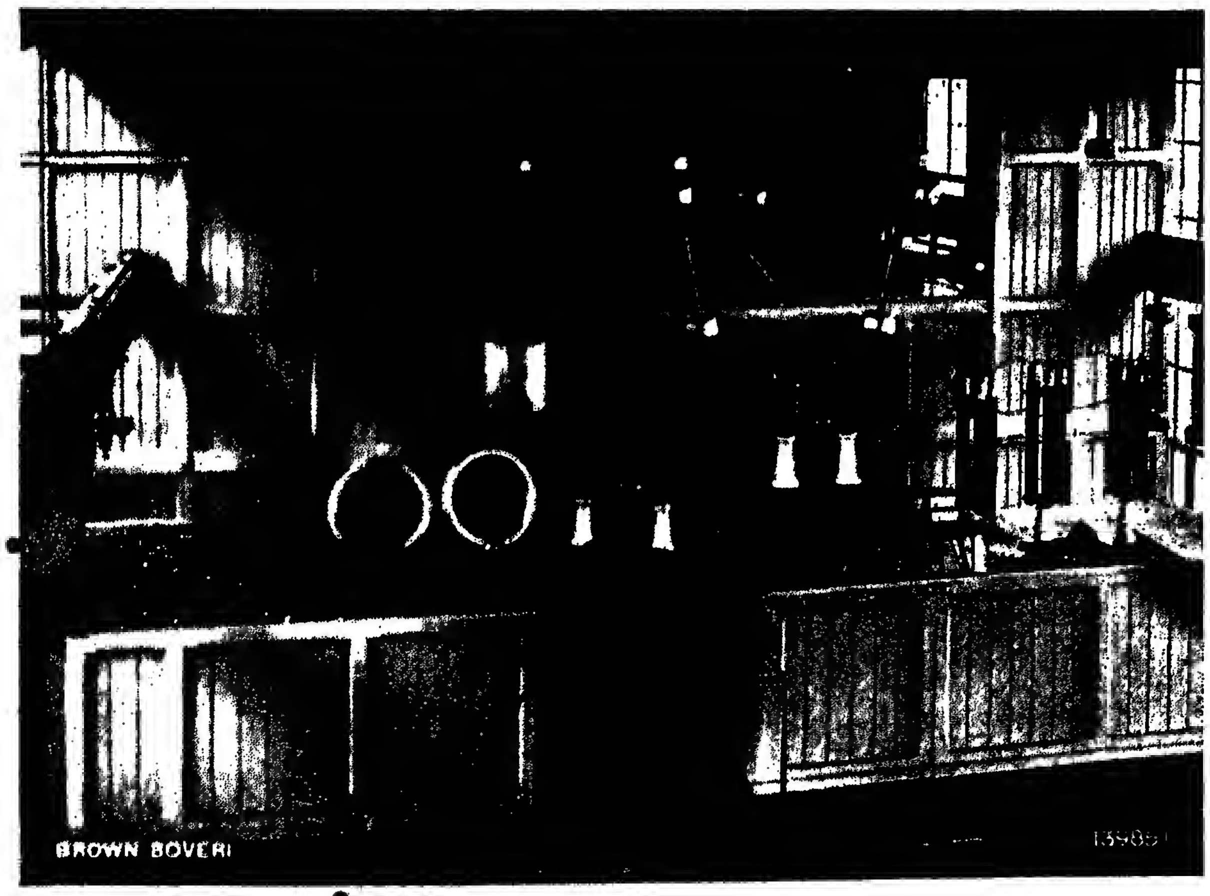


Fig. 44. — **Room for tests on excess-pressure phenomena.**

The transformer is only delivered after it has withstood these tests in all respects, and thus shown itself fit to be put into service.

The enormous developments in the construction of large transformers and the correspondingly heavy stresses put on the materials used necessitate very efficient testing equipment for trying out the finished units. No expense was spared, when the new testing installation was built, to take into account all the conditions

to be met and, in addition to the testing of normal types, to make possible special tests and experimental work. The transformer testing department is, therefore, subdivided into the following sections, to which others can be added later if desired:

(a) Section for normal measurements and load tests on big transformers.

(b) Section for normal measurements and load tests on small transformers.

(c) Dark room for insulation tests on half-finished and finished products either in air, in oil, or under rain, up to a pressure of 500'000 V (Figs. 42 and 43).

(d) Test room for excess-pressure phenomena (Fig. 44).

VIII. TRANSPORT AND ERECTION.

Thanks to suitable design and robust construction, these operations are made very simple. Nevertheless, the heavy weight and high value of the units involved make it necessary for the work to be carried out by experienced men only, of which Brown, Boveri & Co. have always a number at the disposal of their clients. The following paragraphs give a summary of the work entailed by transport and erection on site.

1. Transport and erection on site of transformers ready for use. The work entailed by transport and erection preliminary to putting the transformer into operation differs according to the size of the unit and the conditions on site. For power stations and substations equipped with sidings connected to the main line, the transformers are sent off filled with oil, if the railway loading gauge permits of it.

In such cases, it is only necessary to remove the insulators and take some barrels of oil out of the tank.

Fig. 45 shows a transformer being transported in this way. The transformer is being lifted be means of jacks from one of the firm's crocodile trucks, which has a carrying capacity of 60 tons. Fig. 46 shows the transformer already mounted on a truck and ready to be pushed into position for mounting in its cell. Transport operations of this kind are relatively simple, but the men carrying them out must be experienced and reliable if the possibility of serious damage is to be avoided. If good roads are available and the transformer has a long way to travel, it is possible to place it on a suitable trolley coupled to one or more road tractors. This method of transport can, however, only be used for units up to about 8000 kVA, owing to the heavy loads entailed. On this subject we would refer to

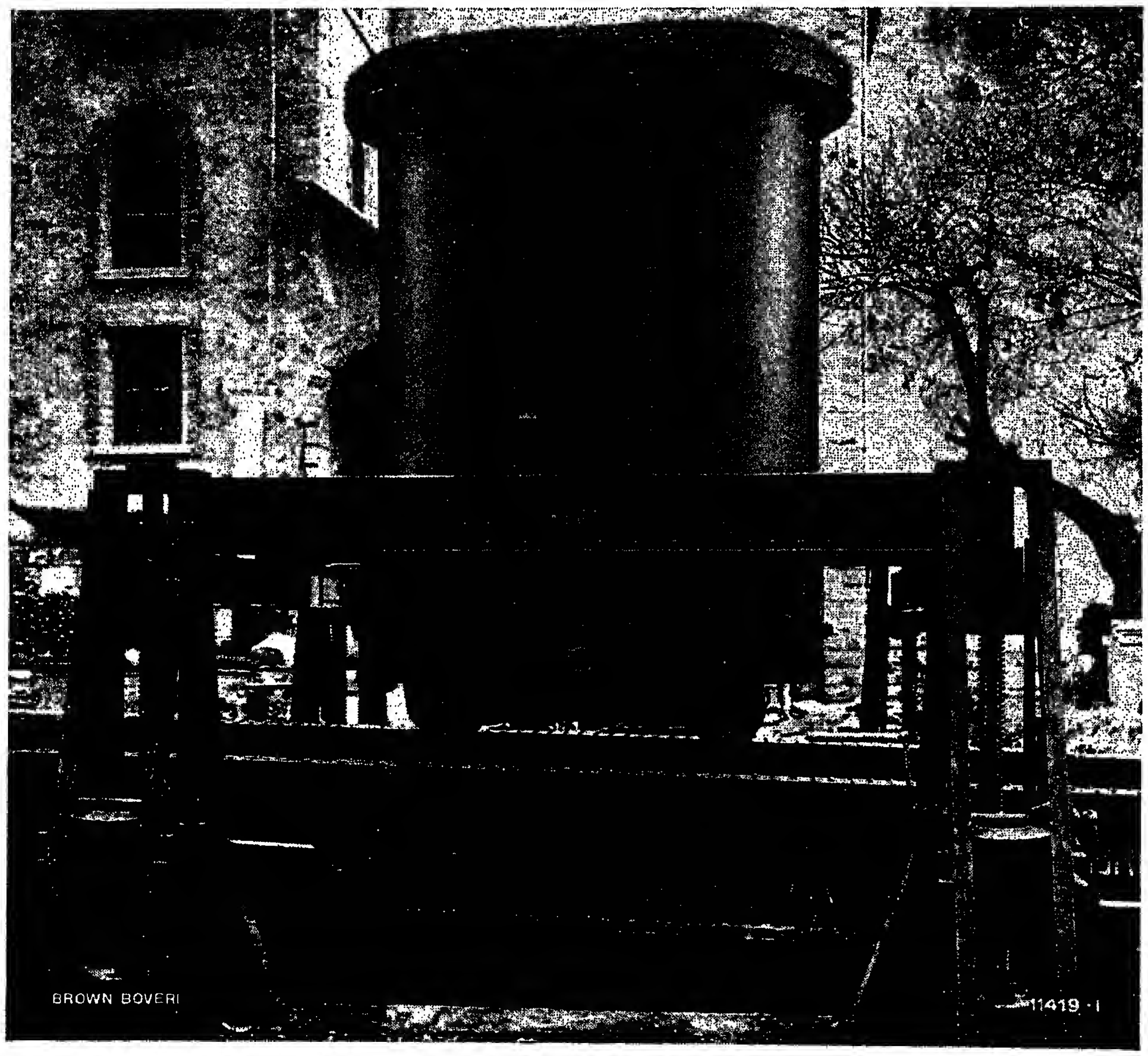


Fig. 45. — Transformer being raised by means of lifting jacks.

Figs. 47 and 48 and to the article in the Brown Boveri Review, 1923, No. 4, entitled "Some notes on the transportation of heavy transformers".

Transformers sent off filled with oil are usually quickly ready for service if the transport conditions have been normal. The insulators have to be replaced and the tank filled up to the indicating mark with that quantity of oil which was sent separately. As a precautionary measure, the insulation between the high and low-tension windings, and between the former and the core should always be tested with a megger or inductor. A sample of the oil must be drawn from as near the bottom of the tank as possible and then tested for moisture in a test tube or by a spark gap. If water has gained access to the oil during transport, the transformer, which was despatched from the works in oil and dried out, must be dried out again.

2. Transport and erection on site of dismantled transformers. It is often impossible to transport the transformers filled with oil and already dried out, as described above, owing to deficient means of transport, bad roads, or special conditions in the power-stations or sub-stations. It is generally possible, at least, to send off the active part in one piece. It may happen, however, that even this part has to be dismantled, in which case the windings and the core are packed in separate cases. After transport, the erection of the transformer requires, of course, more time than when the unit is sent off in the oil and already dried out. Transformers despatched in parts

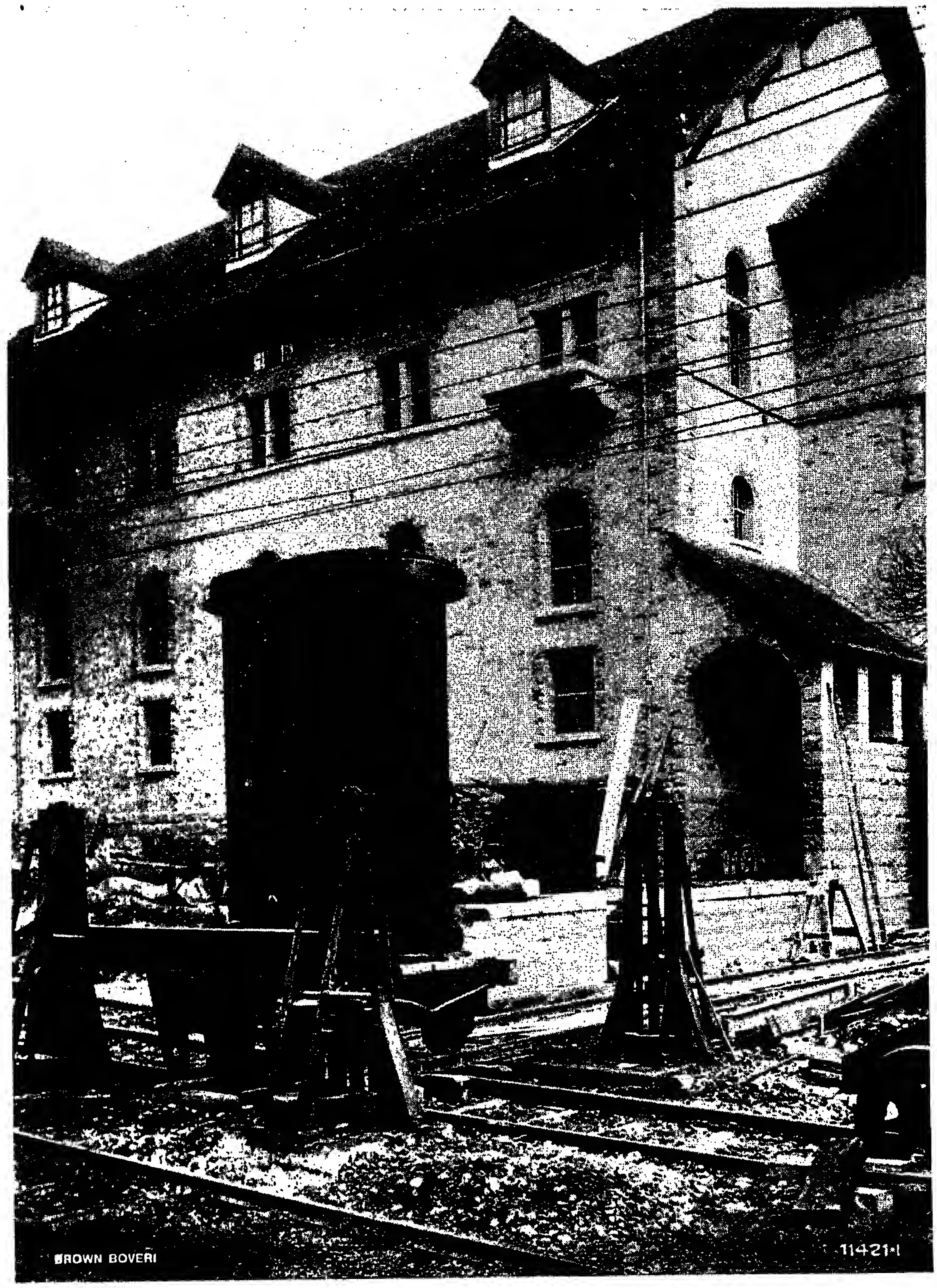


Fig. 46. — Transformer being moved into the substation.

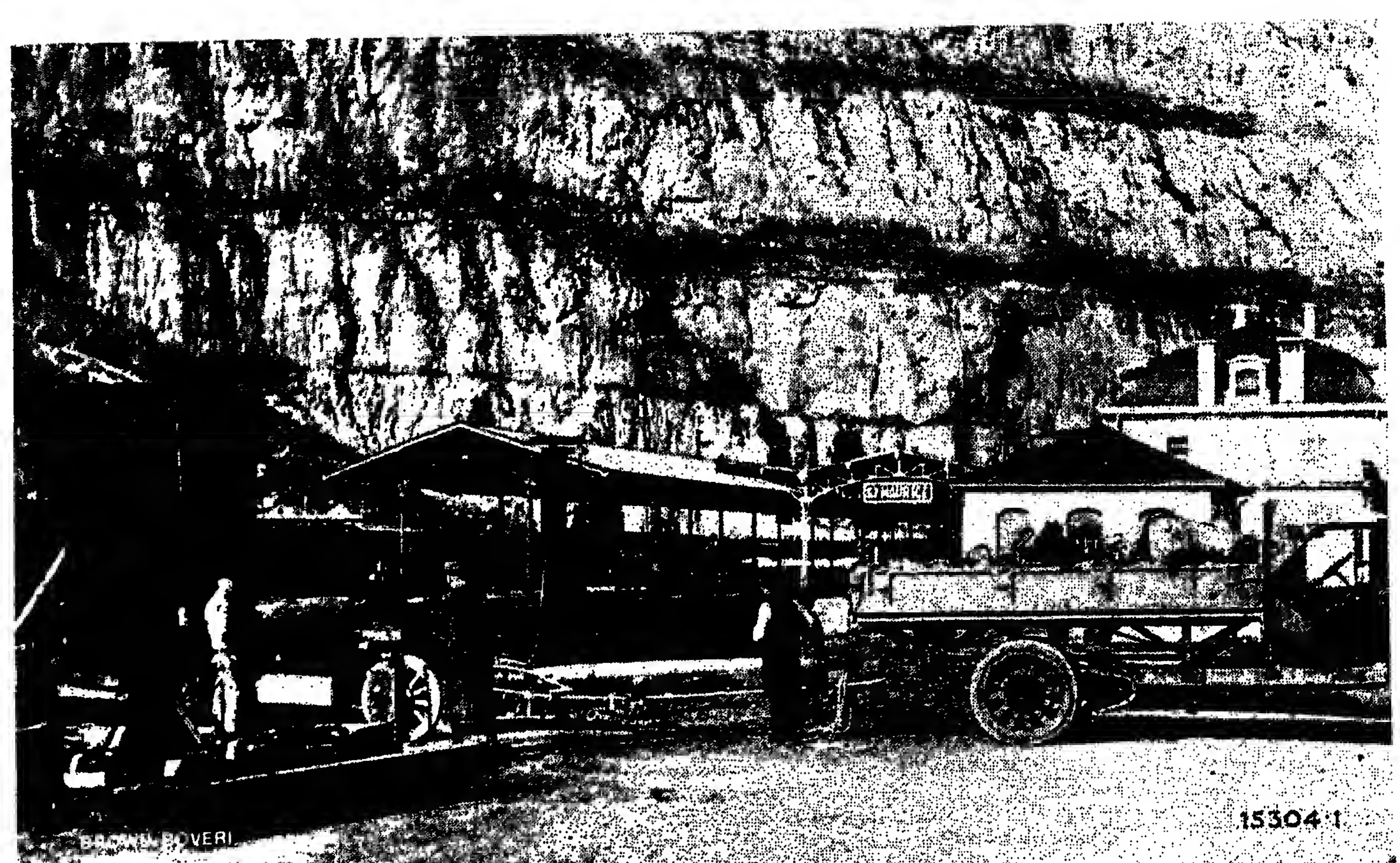


Fig. 47. — Transformer being loaded on to trolley.

have to be put together by special erectors. After this has been done, the transformer must be dried out on site, despite the fact that this work had been done at the works before testing. As already said, efficient drying out is an important factor with regard to the durability of the insulation and reliability of the transformer. It should be noted that all oil-immersed transformers which have been lifted out of the oil for purposes of inspection, for a period of several hours, i. e., up to 12, or at the most two periods not exceeding 24 hours each (according to the pressure and weather conditions), have to be dried out again.

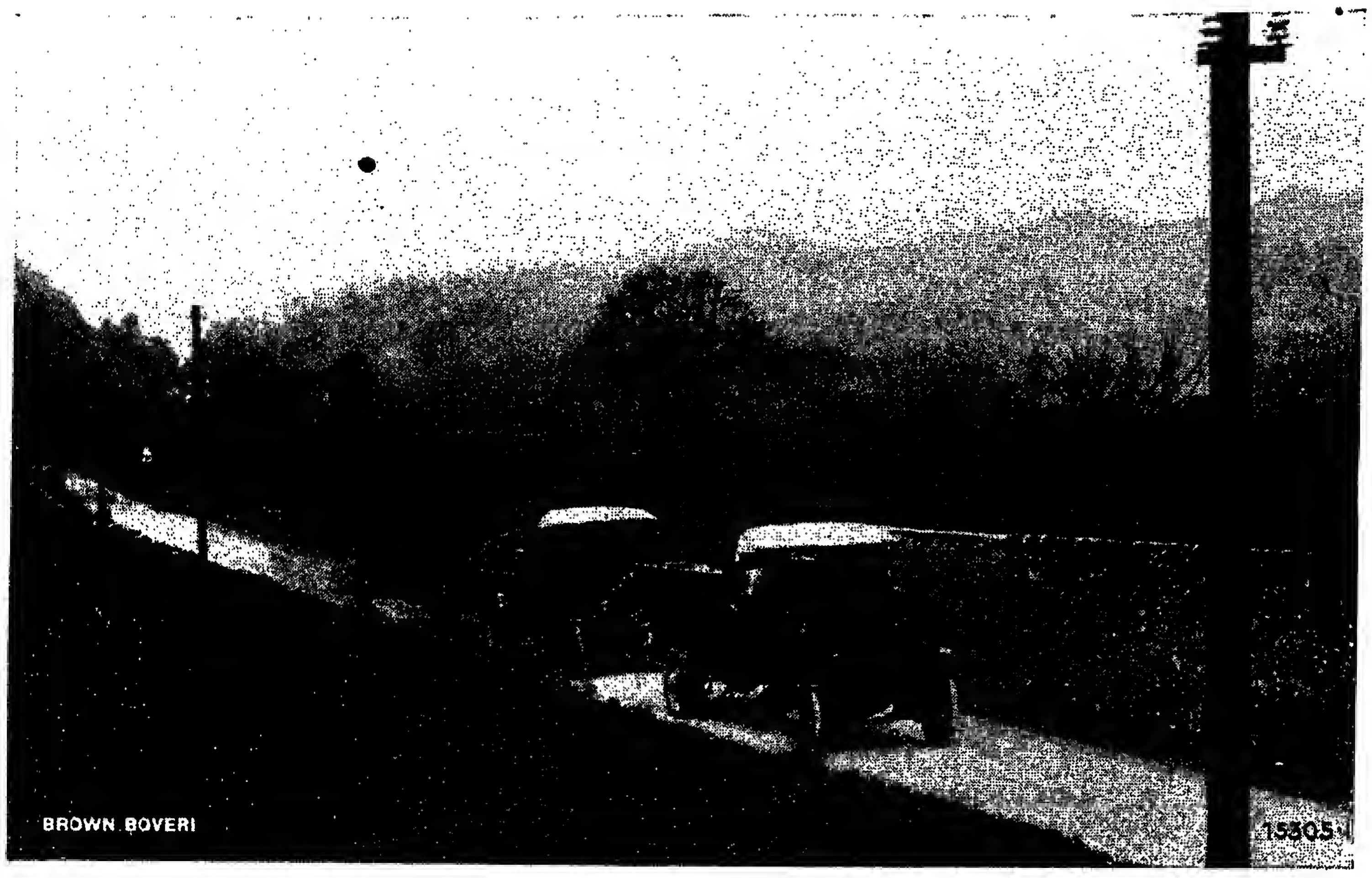


Fig. 48. — Transformer being transported by tractors.

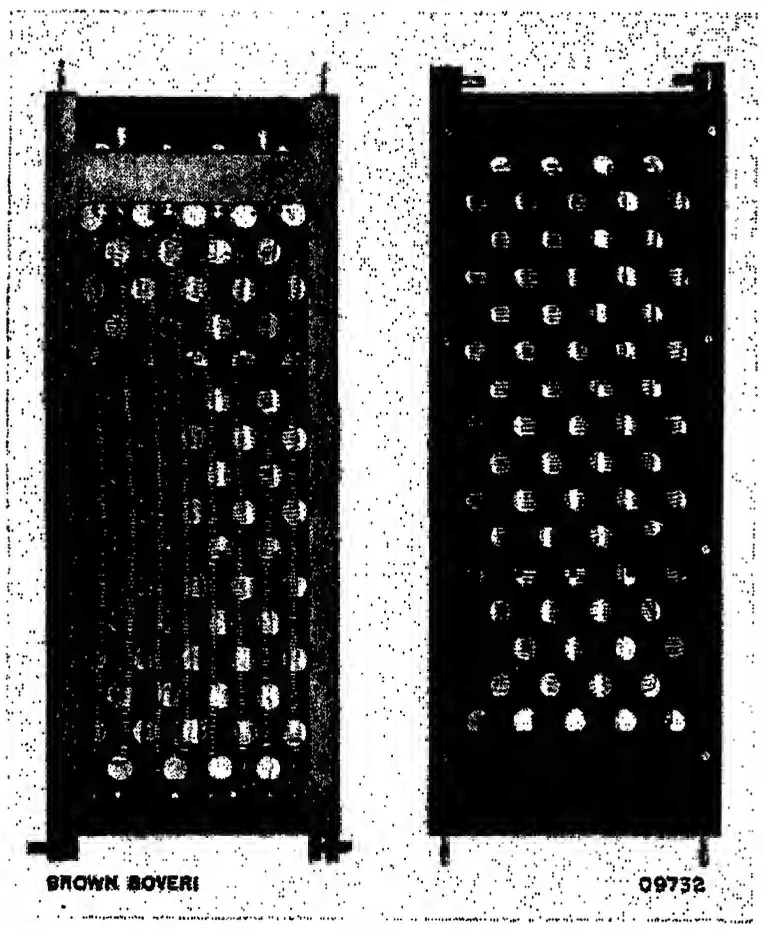


Fig. 49. — Heating elements for drying transformer oil.

The drying-out process can be carried out in very different ways. We give below the methods used by Brown, Boveri & Co. for many years, which have proved most successful.

(a) Drying out by heating resistances placed in the transformer tank.

The resistances are so designed that they can be placed in the narrow spaces remaining between the windings and the inner walls of the tank. The surface of the wire turns forming the resistance is dimensioned so that its temperature is never too great. The heating element shown in Fig. 49 is built in two sizes, namely for 1000 and 2000 watts and can be used either for 55 or 110-V. supply pressure, according to how the connections are made. Several heating elements can be linked up in series, and thus groups are formed for pressures up to 500 V. From the curves given in Fig. 50, the approximate power in kilowatts, and thus the number of heating elements required under normal conditions by any transformer can be determined.

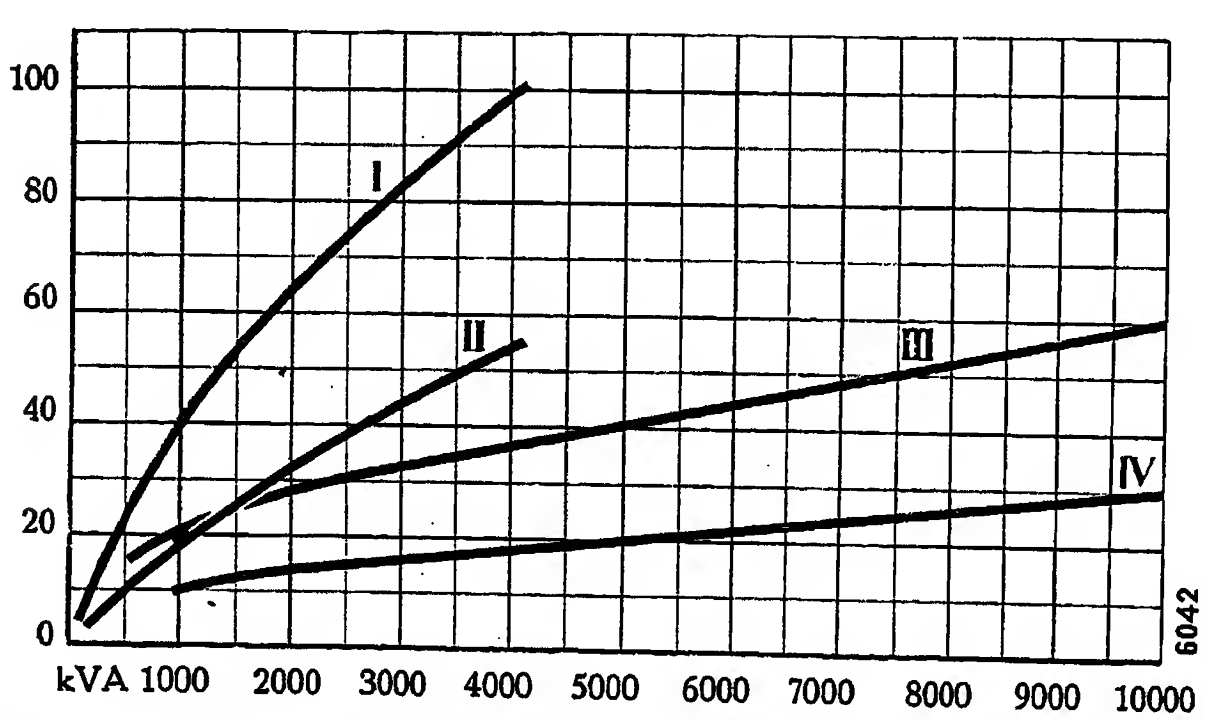


Fig. 50. — Heating power required as a function of the transformer output.

Curves I and II apply to oil-immersed transformers with natural cooling without heat-insulating mats.

Curves III and IV apply to oil-immersed water-cooled transformers, with or without heat-insulating mats.

(b) Drying out by electric oil heater and circulating oil.

The Brown Boveri oil heater, shown in Fig. 51, is provided with heating elements which can be continuously loaded, when under oil, up to 10—40 kW. Drying out with this apparatus is complete and is a

guarantee that, even with damp oil and damp windings, the operation will be thorough. The apparatus can be provided with an automatic temperature regulator. When this is used, less supervision is necessary and heating of the oil above the allowable temperature is less likely to occur.

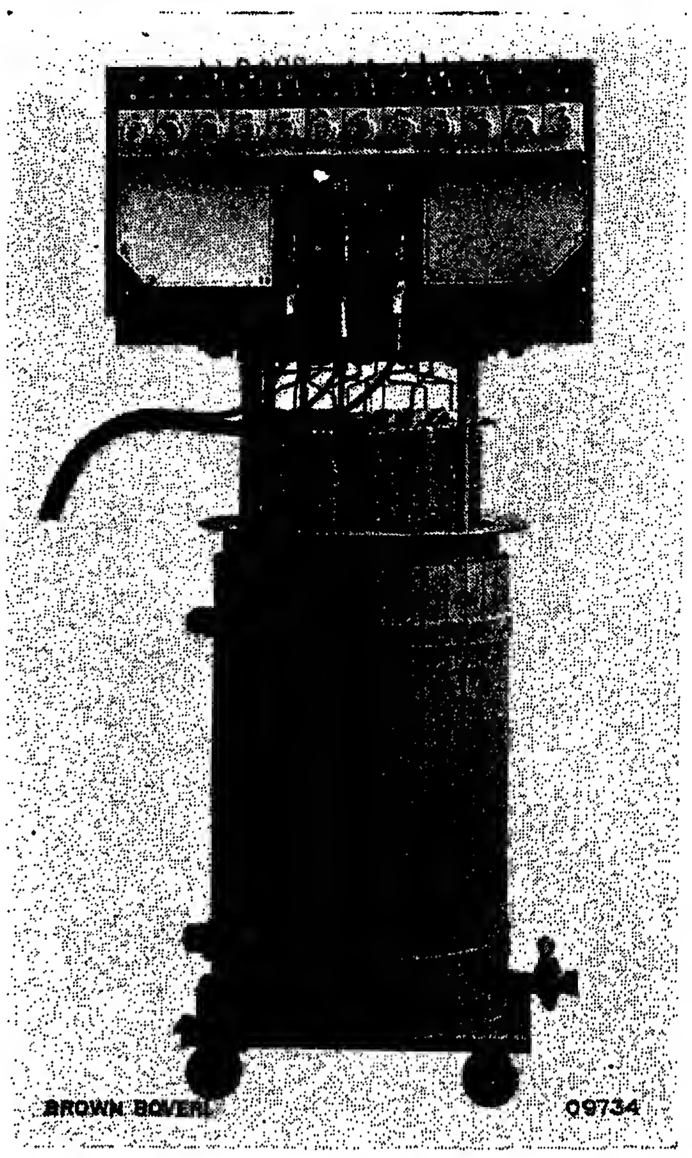


Fig. 51. — Oil-heater.

(c) Drying out with air excluded (cork-granule process).

With ordinary drying-out methods, the hot oil comes into contact with the oxygen of the air and is thus oxidised. For many years, Brown Boveri & Co. have been using with great success a process by which the surface of the oil in the tank is covered by a layer of cork granules 10 to 15 cm thick, the cork used being first dried, cleaned, and specially treated (Fig. 52). Thorough tests in the firm's laboratories enabled the most suitable size of granule, thickness of the layer, and best preliminary treatment of the cork to be determined. The results showed that, when the process is properly carried out, the oil is as well protected as when dried out under a vacuum.

Before the granules are poured on to the surface of the oil, a piece of quite smooth cotton cloth is laid over the oil. Care must be taken that the cloth covers the whole surface so that no air pockets are formed between the cork and the oil. This process has the advantage of being applicable in all cases.

(d) Drying out with air completely excluded.

Drying out in vacuo is the most complete process possible. The separation of the damp and air from the oil, windings, and insulating parts takes place more easily under a pressure less than atmosperic, at moderate temperatures. The low drying-out temperature, the short time required for the process, and the complete exclusion of air are factors favorable to the durability of the oil and of the insulation. There are various methods of drying out under vacuum. The transformer tank itself can be built as a vacuum vessel, or the whole transformer, with tank and oil filling, can be placed in a vacuum chamber. In both cases, a Brown Boveri combined oil-vacuum pump (Fig. 54) is used to advantage, and the oil heated in the oil heater described under (b). If no such heater be available, the oil can, of course, be heated by resistances which are built into the tank as described under (a).

There are other ways of drying out transformers as, for example, over an open fire and the drying of the active part separately without oil. Details of these methods are unnecessary as they should be very seldom used and only

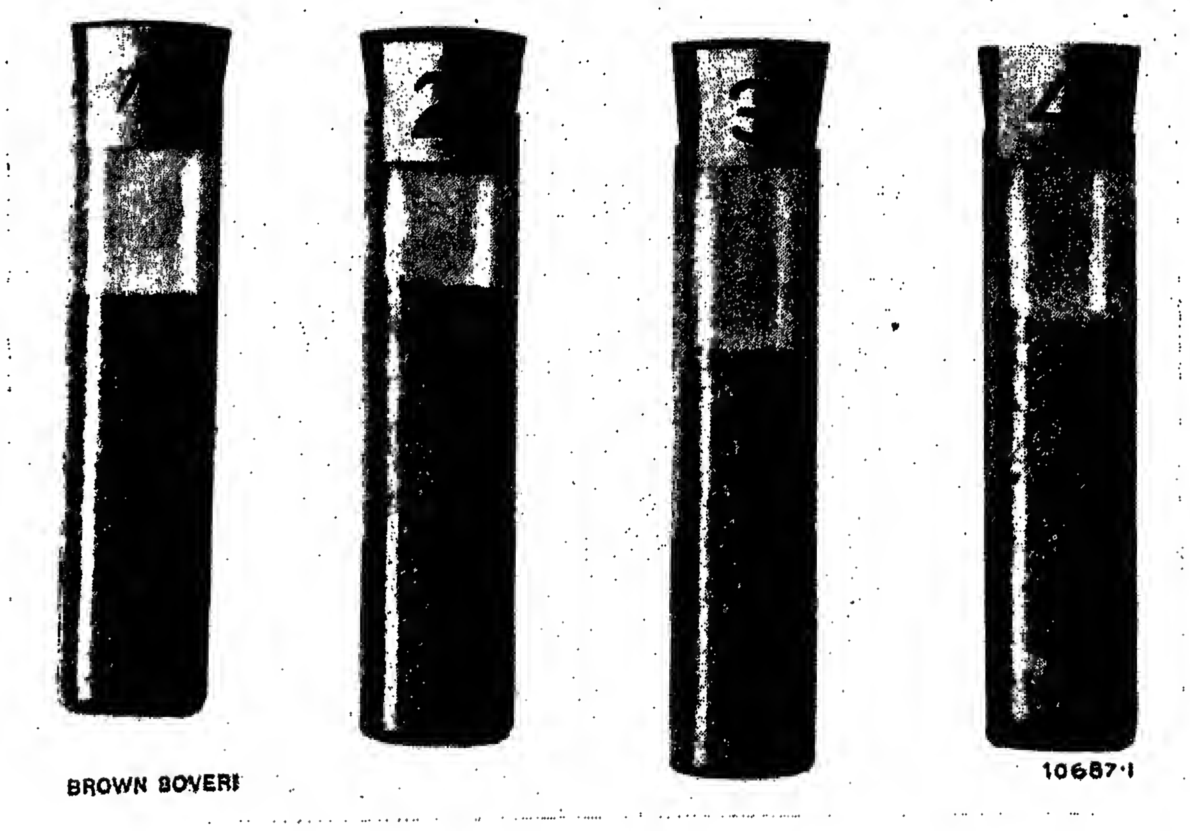


Fig. 52. — Cork granules of different sizes. No. 3 is the most satisfactory.

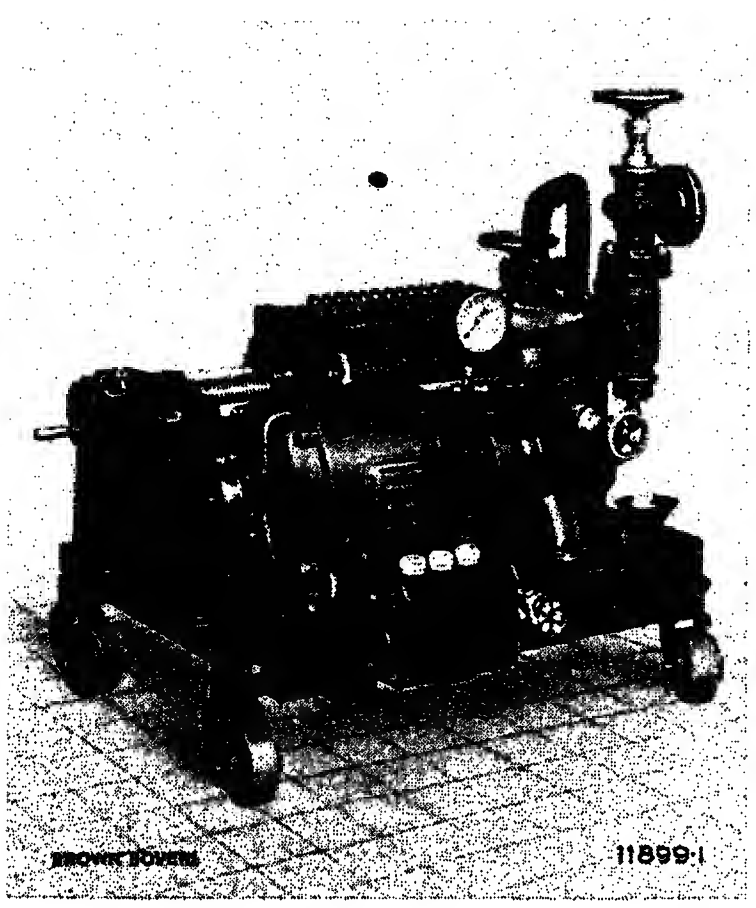


Fig. 53. — Brown Boveri oil-filtering apparatus.

carried out by experienced personnel. Further, it is practically always possible to have recourse to one of the better methods just described.

3. Inspection and work to be done after drying out and before putting into service. Under certain conditions, the height of the windings may be reduced as a result of contraction of the insulating parts during the drying-out process. It is, therefore, necessary to take out the dried active part, *after it has cooled to at least 50° C.* in order to inspect the windings and, if necessary, to tighten up the winding supports. If the windings be provided with the Brown Boveri patent short-circuit-proof winding supports, this is a very simple matter, and means only that the springs must be screwed up until they exercise a given pressure. With high-tension transformers, it is desirable to filter the oil of the transformer, now ready for service and dried out, immediately after the above described operation. This must always be done if cork has been employed in the drying out. Some years back, Brown, Boveri & Co. placed on the market a suitable filter press, which can also be used with advantage to dry out the oil (Fig. 53). Once all these operations have been carried out, and after an inspection of the cooling apparatus, the transformer can be put into operation.

As mentioned at the beginning, there are various cooling devices, most of which require certain preliminary work before being ready for service. Transformers with natural oil cooling need no further inspection in this respect. With internal water cooling, however, an inspection must be made to see if, when the transformer is cold, the cooling apparatus is completely immersed in the oil. The tubes by which the cooling water is led in and out, and which extend above the surface of the oil, must be covered by a double layer of felt and tape to prevent the condensation of moisture. Before connecting to the water main, each cooler must be tested as to water tightness. This test is carried out under oil with an air pressure of 3 kg/cm². Cooling with external oil circulation (the oil passing through a separate water cooler) is, generally speaking, preferable to internal water cooling. The danger of water percolating through to the oil, if the cooler be damaged is prevented if erection has been well carried out. The external oil cooler must also be tested under an air pressure of 3 kg/cm² before it is connected to the transformer. Before being put into service, the transformer tank and core are to be effectively earthed.

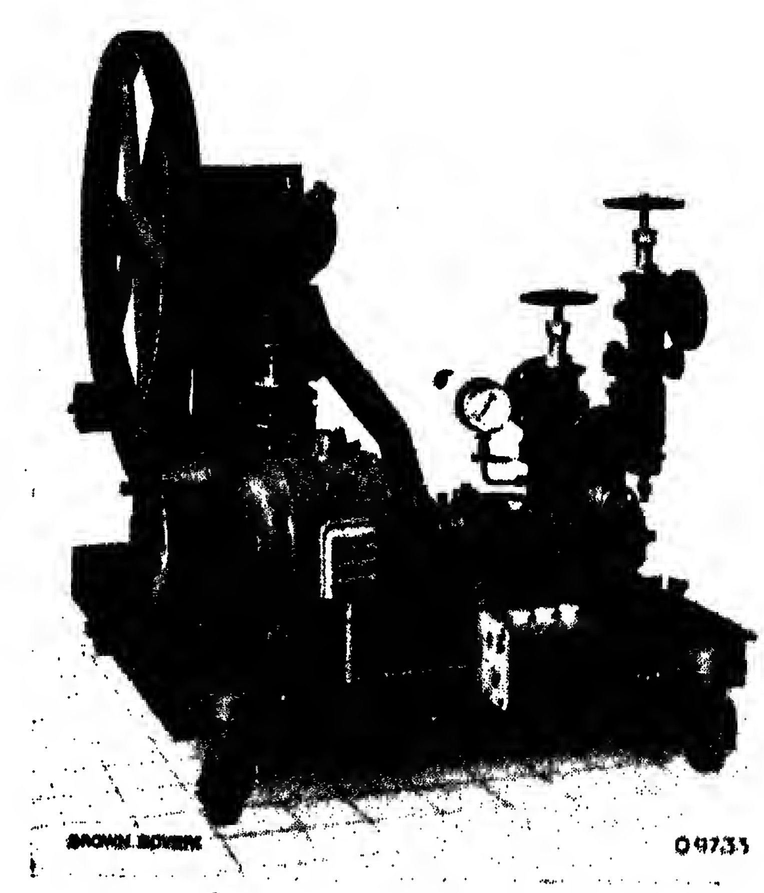


Fig. 54. — Brown Boveri combined oil vacuum pump.

All the erection operations carried out on site are described above; those applying to each individual case depend upon the method of transport adopted. After making the necessary connections, the transformer can be put under pressure and loaded.

IX. SERVICE INSTRUCTIONS.

Realiable supervision is an important factor for transformers, as for other apparatus and machinery, and this is especially the case with transformers of large outputs. For this reason, all transformers delivered are accompanied by special instructions for handling and operation, which are based on the practical experience of many years. Supervision consists in periodic tests and inspection. This means a certain amount of work which, however, is richly repaid by fewer interruptions in working, and a lengthening of the life of the transformer. It is advantageous to keep an account of the tests in order to be immediately aware of any irregularities which may appear in operation. Supervision may be subdivided into daily, monthly and yearly tests.

The daily supervision only consists in measuring the temperature of the oil, windings and cooling water. The normal oil temperature measured in the upper layers of oil should not in general exceed 65—80° C, 65° C applying to units with artificial cooling and 80° C to units with natural cooling. With transformers having artificial cooling, the water-circulation alarm device, the oil-flow meter, etc. should be rapidly inspected two or three times a day, preferably between shifts.

The quantity of cooling water required in transformers with internal water cooling is about 0·9 litres per minute for each kilowatt of losses. The temperature of the water at the inlet should not be more than 15—20° C and that at the outlet 30—35° C at the highest. When the transformer is cut out, the water flow should be stopped. If there is any danger of freezing, however, either the water should not be cut off, or else the oil of the transformer must be kept above freezing point by means of heating resistances. If this also is impossible, the piping is empted and the cooler blown out by air under pressure. The same measures are to be taken with transformers with external oil circulation as with those with internal water cooling. Transformers with natural cooling require no special measures in this respect.

The monthly supervision is made with the help of the daily service journal. The quantity of cooling water, the temperature differences between the water at the inlet and the outlet, and the quantity of heat carried off are noted for identical loads. If, in the course of time, the temperature of the oil increases while the pressure and load conditions remain the same, the quantity of heat carried off remaining constant, this is a sign that the cooler is dirty. If, on the contrary, the temperature of the oil increases and the quantity of heat carried off also increases, this shows that a fault exists somewhere in the transformer. During the monthly tests the humming of the transformer should be considered. If this sound has increased, compared with earlier observations, a fault must have developed in the transformer, and the cause must, under all circumstances, be found out.

Once a month, all signalling devices, such as water-circulation alarms, contact thermometers, oil-flow meters, etc. must be tested to make sure that they are functioning correctly. It is also desirable, once a month, to allow the switch releasing devices to act and to ascertain that the relays are properly set.

The annual tests are more in the nature of an overhaul and, in the interest of good service, should not be omitted. A year after setting to work, and subsequently every two years, the transformer should be submitted to a *general overhaul*, The active part is lifted out of the oil and the windings, core, oil, insulators and the auxiliary apparatus are thoroughly tested. If sludge has formed, the oil and the windings, core and cooler are to be thoroughly cleaned. The sludge adhering

to the windings and iron is to be removed by means of a powerful jet of hot oil (at about 50 °C). The tank and insulators are best cleaned with cotton waste. The oil containing sludge is to be filtered. To clean the oil, the best method is to use the filter-press, with the help of which dirty oil and also oil containing moisture is easily brought back to good condition. If, after a long service period, there is a loss of oil, the quantity must be made up only with the same quality of oil as was used at the first filling. Even small additions of unsuitable oil are sufficient to ruin a large quantity of good oil. If the cooler has become coated internally with sludge, the best method of cleaning is to use a steam jet or Benzol. The cooling-water coils in transformers with internal water cooling should be tested under a pressure of 3 kg/cm² during the annual overhaul. If a leak be discovered in a cooling coil, the whole transformer must be dried out again, because it is usually impossible to be certain that no water has percolated into the oil.

Experience shows that, when cooling water does not contain an exceptional quantity of lime, a thorough cleaning of the cooler will be necessary every four or five years. Scale and deposits which have formed in the cooling pipes are best dissolved by spraying a 5—10 % solution of hydrochloric acid into the piping. The solution must be left in the tubes only until the evolution of gas ceases, when it must be expelled to avoid corrosion of the piping. The piping must immediately be cleaned out with a solution of caustic potash or caustic soda, and then with water. Internal coolers having tubes galvanised on both sides, must be re-galvanised after this operation. During the annual overhaul, all washers and packings must be inspected and, if necessary, renewed with cardboard soaked in linseed oil. Packings containing rubber cannot usually be considered oil tight. If faulty oil-pump glands are discovered, and tightening fails to remedy the defect, new cotton-waste packing must be put in. See the Brown Boveri Review, 1923, No. 1, "Methods for cleaning coolers of large transformers".

If these measures for upkeep are carried out with transformers in service, and especially with units for large outputs, there is every reason to be confident of reliability for a period of many years.

X. SUMMARY OF THE PRINCIPLES FOLLOWED BY BROWN, BOVERI & CO. IN THE CONSTRUCTION OF TRANSFORMERS FOR LARGE OUTPUTS.

The following is a short summary of the principles, which are the result of painstaking study, tests, and knowledge gained by wide experience:—

1. Transformer tanks specially designed to be absolutely oil-tight and pressure-proof, for units with natural and artificial cooling.
2. Suitable design and careful building up of the iron core so as to avoid, as far as possible, additional losses and their disadvantages.
3. Intensive cooling of cores and yokes ensured by patent method of construction.
4. Utilisation of circular coils to avoid radial bending stresses.
5. Patent spring winding supports to eliminate axial shocks during short circuits and their consequences.
6. Ample cooling facilities for windings and little difference between the temperatures of the hottest spot and the mean temperature of the oil.
7. Special construction of the tapping connections.
8. Special construction of the bushings.
9. Damp-proof and air-tight construction for outdoor transformers.
10. Special measures to facilitate transport and erection.
11. Limiting of current and pressure surges by low flux density in the core and appropriate connections.
12. Great internal and external insulation strength of the windings effected by extensive subdivision of the coils, heavy insulation, and the employment of protective rings.
13. Avoidance of additional copper losses by the choice of a suitable copper section.
14. Impregnation of coils making them impervious to oil and able to withstand heat.
15. Carefully designed cooling system, protective apparatus, and control gear.
16. Utilisation of oil of high grades, which does not affect the insulation, and is capable of withstanding heat.
17. Thorough testing of all raw material, suitable manufacturing processes, and continuous supervision during manufacture.
18. Perfectly equipped testing department and laboratories for testing half-finished and completed parts, and for making special tests.
19. Utilisation of efficient processes for drying out transformers in the shops or on site.

XI. SOME IMPORTANT BROWN BOVERI TRANSFORMERS FOR LARGE OUTPUTS AND HIGH TENSIONS.

No.	Client	Plant	No. of units	Output per unit in kVA	Pressure Ratio V	Connections	Frequency	Date of order
	A. Transformers for outputs of over 10'000 kVA or tensions higher than 60'000 V.							
1	Soc. Meridionale di Elettr. Naples	Pescara	9	3600*	6600/88 000	△/Y	42	1910
2	Eisenbahndirektion Halle S.	Muldenstein	2	2000*	3400/64 160	—	$16\frac{2}{3}$	1910
3	Mines de la Houve, Creutzwald	Creutzwald (Lorraine)	5	3750	10 500/66 000	Y/Y	50	1911
4	A. G. Motor, Baden	Bottmingen	2	4000	68 500/57 000	Y/Y	50	1912
5	Sté Hydro-Electrique de Lyons	Poste de la Mouche	4	4000	64 000/11 000	Y/Y	50	1913
6	Kraftwerk Laufenburg	Laufenburg	2	10 400	6700/74 200	△/Y	50	1913
7	A. G. Motor, Baden	Bottmingen	1	4000	68 500/57 000	Y/Y	50	1914
8	Badenwerk, Karlsruhe	Transf. Stat. Rheinau	2	5000	100 000/22 000	Y/Y	50	1917
9	Sté Hydro-Electrique de Lyons	Centrale des Portes du Fier à Seyssel	4	4500	11 000/70 000	Y/Y	50	1917
10	Eléctra de Viesgo, Santander	Camarmena	2	7000	5100/100 000	Y/Y	50	1918
11	Eléctra de Viesgo, Santander	Reinosa, Const. Navales	5	3000	92 150/3400	Y/Y	50	1918
12	Eléctra de Viesgo, Santander	Urdon	1	6000	95 000/5000	Y/Y	50	1918
13	Eléctra de Viesgo, Santander	Punte San Miguel	1	6000	93 000/60 000	Y/Y	50	1918
14	Elektrizitätswerk Olten-Aarburg	Olten-Gösgen	2	7050	8860/77 370	Y/Y	50	1918
15	Swiss Federal Railways, Berne	Giornico	2	5000*	60 000/15 000	—	$16\frac{2}{3}$	1918
16	Union d'Electricité, Paris	Poste d'Argenteuil	4	4000	5250/60 000	Y/Y	50	1919
17	Entreprises Electr. Fribourgeoises	La Jogne	4	5300	9700/64 700	Y/Y	50	1919
18	Swiss Federal Railways, Berne	Melide	2	5000*	60 000/15 000	—	$16\frac{2}{3}$	1919
19	Energie Electr. de Meuse et Marne, St. Dizier	Poste de Ligny en Barrois	2	5000	65 000/30 000	Y/Y	50	1920
20	Cie des Mines de Vicoigne, Nœux et Drocourt	Centrale de Beuvry (Pas de Calais)	3	12 500	5250/15 750	Y/Y	50	1920
21	Deutsche Contin. Gas-Gesellsch., Dessau	Transf. Stat. Magdeburg	2	10 000	105 000/56 000	Y/Y	50	1920
22	Soc. El. del Moncenisio, Turin	Venaus	2	24 000	6660/75 600	△/Y	50	1920

* Single-phase transformers.

No.	Client	Plant	No. of units	Output per unit in kVA	Pressure Ratio V	Connections	Frequency	Date of order
23	Soc. El. del Moncenisio, Turin	Turin	2	22 000	65 500/2400	火/火	50	1920
24	Soc. Ital. per l'Utilizz. delle Forze Idrauliche del Veneto, Venice	Santa Croce	2	22 000	6600/62 700	人/火	42	1920
25	Schweiz. Kraftübertragungs-A. G., Berne	Amsteg	1	13 000	$\frac{8600—7835}{84\,300}$	△/火	50	1921
26	Sté Hydro-Electrique de Lyons	Poste de la Mouche (Rhône)	1	8000	61 000/10 000	人/人	50	1921
27	Elektrizitätswerk Stettin	Stettin Zentrale II	1	16 000	$\frac{16\,250—15\,500}{5247}$	火/火	50	1921
28	Bayernwerk A.-G., Munich	Würzburg Schweinfurt Aschaffenburg	2 2 2	6000 6000 6000	112 000/23 130 112 000/23 130 112 000/23 130	火/△ 火/△ 火/△	50	1921
29	Midi Railway Company, Paris	Pau, Lourdes, Tarbes, Lannemezan, Montréjeau	16	2250	$\frac{60\,000}{12\times1250}$	人/12 Ph	50	1921
30	Midi Railway Company, Paris	Coarraze-Nay et Tournay	7	1200	$\frac{60\,000}{1250}$	人/=	50	1922
31	Cie Hydro-Electrique d'Auvergne, Paris	Centrale de Condes sur Allier	2	13 000	3150/65 500	人/人	50	1922
32	Cie Hydro-Electrique d'Auvergne, Paris	Poste de Clermont-Ferrand	2	10 000	62 000/3500	人/△	50	1922
33	Ferrovie dello Stato, Rome	Genoa-Pisa	40	750	$\frac{66\,000}{4290—3700}$	△/△	$16^2/_3$	1922
34	E. W. Olten-Aarburg, Olten	Olten-Gösgen	1	15 000	8600/138 000	△/火	50	1922
35	Soc. delle Forze Idrauliche dello Alto Brembo, Milan	Corona	1	15 000	8800/135 300	△/火	50	1922
36	Soc. Elettr. Bresciana, Brescia	Brescia	1	8000	$\frac{10\,925—12\,075}{68\,000}$	人/火	42	1922
37	Soc. Gen. It. Edison, Milan	Impianto di Sesto	1	7000	$\frac{59\,000}{22\,200—23\,800}$	人/人	42	1922
38	Entreprises Electr. Fribourgeoises	Hauterive	1	6000	9330/65 300	人/人	50	1922
39	Zentralschweizer. Kraftwerke Lucerne	Lake Lungern	1	12 500	$\frac{8700—8100}{57\,000}$	△/人	50	1922
40	Soc. Lombarda per Distribuzione di En. El., Milan	Parabiago	1	10 000	$\frac{69\,000}{47\,600—43\,500}$	人/人	50	1922
41	Forces Motrices du Haut-Rhin, Mulhouse	Ile Napoléon	1	5000	$\frac{70\,000}{22\,630—20\,340}$	人/人	50	1922

* Single-phase transformers.

No.	Client	Plant	No. of units	Output per unit in kVA	Pressure Ratio V	Connections	Frequency	Date of order
42	Stamperia It. E. de Angeli, Milan	Legnano	4	5500	10 000/75 000	Y/Z	50	1923
43	Stamperia It. E. de Angeli, Milan	Legnano	1	2000	3300/75 000	Y/Z	50	1923
44	Stamperia It. E. de Angeli, Milan	Legnano	5	4500	70 000/550	Y/Z	50	1923
45	Soc. Lombarda p. Dist. di Energia Elettrica, Milan	Castellanza	2	16 600	47 000/12 700—11 600	Y/Y	50	1923
46	Soc. Adriat. di El., Venice	Verona	1	5100	63 000/11 500—10 500	Y/Y	50	1923
47	Kraftwerk Wäggital A.-G., Zurich	Siebnen und Rempen	6	16 500	8800—9560/50 000	Δ/Z	50	1923
48	Kraftwerk Wäggital A.-G., Zurich	Siebnen	2	16 500	9700—10 500/160 000	Δ/Z	50	1923
49	Soc. Gen. It. Edison di El., Milan	Rovesca e Pallanzena	4	12 000	8940—8280/143 500	Δ/Z	50	1923
50	Soc. Ligure Tosc. di El., Livorno	Ponticosi	3	3000	5750/65 550	Y/Y	50	1923
51	Soc. Ligure Tosc. di El., Livorno	Gallicano	1	6000	5750/65 550	Y/Y	50	1923
52	Soc. Idroel. del Piemonte, Turin	Turin	2	12 500	68 000/24 300—23 300	Z/Y	50	1923
53	Soc. Idroel. del Piemonte, Turin	Aosta	2	15 000	47 000—45 000/80 000	Y/Y	50	1923
54	Soc. Anglo-Romana, Rome	Terni	1	12 000	6700/66 000	Y/Z	45	1923
55	Soc. Meridionale di Elettricità, Rome and Naples	Torre Annunziata	2	4000	60 000/29 000—27 000	Y/Y	45	1923
56	Soc. Meridionale di Elettricità, Rome and Naples	Torre Annunziata	5	4000	60 000—56 000/12 600	Y/Y	45	1923
57	Soc. Dynamo per Imprese Elettriche, Milan	Varzo	1	12 500	3800/53 000	Y/Y	50	1923
58	Soc. Idroelettrica Cisalpina, Milan	Mese	2	30 000	8400/150 000	Δ/Z	42	1923
59	Soc. Lyonnaise des Forces Motrices du Rhône, Lyons	Lyons	4	6666*	120 000/10 000	Y/Δ	50	1923
60	Elektrizitätswerk Bukarest	Grosaveşti	1	5000	60 000/5500—5000	Z/Δ	50	1923
61	Nordostschw. Kraftwerke, Baden	Beznau	3	5000*	150 000/44 500—47 500	Y/Δ	50	1923

* Single-phase transformers.

No.	Client	Plant	No. of units	Output per unit in kVA	Pressure Ratio V	Connections	Frequency	Date of order

B. Outdoor transformers.

No.	Client	Plant	No. of units	Output per unit in kVA	Pressure Ratio V	Connections	Frequency	Date of order
1	Soc. Meridionale di El., Naples	Matese	3	12 000	10 600/68 000	△/Y	42	1921
2	Soc. El. Interregionale, Milan .	Brugherio	4	10 000*	22 500/127 500	△/Y	42	1921
3	Soc. El. Interregionale, Milan .	Reggio Emilia	2	9000	122 000/62 000	Z/Z	42	1922
4	Swiss Federal Railways, Berne	Puidoux	2	5000*	60 000/15 000	—	$16^2/_3$	1922
5	Swiss Federal Railways, Berne	Emmenbrücke	3	3000*	60 000/15 000	—	$16^2/_3$	1922
6	Schweiz. Kraftübertragungs-A. G., Berne	Olten-Gösgen and Rathausen	7	4330*	$\frac{78\,000-65\,300}{52\,000-46\,800}$	Y/△	50	1922
7	Cie d'Entreprises Electro-Mécaniques, Paris	Los Almadenes . . .	4	3700*	5000/65 000	△/Y	50	1922
8	Comptoir Central d'Achats, Paris	Millery (Meurthe et Moselle)	2	3000	65 000/17 300	Y/△	50	1922
9	Schweiz. Eisenbahnbank, Basel	Tüffer (Jugo Slavia) . .	3	3000	$\frac{82\,500}{35\,000 \pm 4\,\%}$	Y/△	50	1922
10	Coop. de Fluido Eléctrico, Barcelona	San Tirs	4	10 000	6000/110 000	△/Z	50	1923
11	Coop. de Fluido Eléctrico, Barcelona	San Andrés	2	10 000	104 000/25 000	Y/△	50	1923
12	Coop. de Fluido Eléctrico, Barcelona	San Andrés	3	5000	104 000/25 000	Y/△	50	1923
13	Coop. de Fluido Eléctrico, Barcelona	Manso-Figueras	3	5000	104 000/25 000	Z/△	50	1923
14	Swiss Federal Railways, Berne	Brugg	3	3000*	60 000/15 000	—	$16^2/_3$	1923
15	Swiss Federal Railways, Berne	Bussigny	3	3000*	60 000/15 000	—	$16^2/_3$	1923
16	Ministère des Travaux Publics, Paris	Paris	7	2500*	120 000/68 250	Y/△	50	1923
17	Aluminium Ind. A. G., Neuhausen	Turtmann	5	8400	9250/60 000	Y/Z	50	1923

* Single-phase transformers.

BROWN BOVERI
SMALL TRANSFORMERS

BROWN, BOVERI & COMPANY
LIMITED
BADEN (Switzerland)

890 E – III 2
(1944)

March, 1926

BROWN BOVERI

SMALL TRANSFORMERS

INTRODUCTION

Research and practical experience have enabled noteworthy improvements to be made in the construction of both large and small transformers during the last few years. Even in designs upon which much care has been spent, every consideration corresponding to the development of technical knowledge is, however, only rarely included. An alteration in the fundamental principles of the original design necessitates new types. Owing to the trend of events Messrs. Brown, Boveri & Co. have placed on the market a new series of small transformers.

These new transformers are fitted with circular coils, similar to those of all large transformers made by Brown, Boveri & Co. The coils are made with constant curvature, as rectangular coils cannot fully satisfy the conditions owing to physical reasons which apply both mechanically and electrically. The new coils are composed of individual elements, each one being specially constructed; their principal feature is electrical and mechanical strength. Very low no-load losses and exceptionally small no-load currents are improvements of considerable importance which are characteristic of these transformers.

METHOD OF COOLING TRANSFORMERS

The earliest types of transformers were air cooled. This type seems to possess the advantages of simplicity and of accessibility to the windings, when compared with the special tank and oil filling required for an oil-immersed transformer; hence, it often seems justifiable to prefer air-cooled to oil-immersed transformers.

Dr. L. C. Brown, one of the founders of this firm, introduced into practice the oil-immersed transformer, the design of which he personally developed. The importance of this invention, and its extensive application is particularly emphasised by the extraordinarily large numbers of transformers of this type produced by important firms all over the world.

At present, the more recently invented oil-immersed transformer has almost entirely supplanted those of the air-cooled type. Except for a few special purposes for which air-cooled transformers are still used, Brown, Boveri & Co. build oil-immersed transformers exclusively. Oil-immersed transformers are now constructed for applications in which previously air-cooled transformers were almost entirely employed.

The following are the principal reasons for preferring oil-immersed transformers: —

1. The dielectric strength of oil-immersed transformers is far higher than that of the air-cooled types; hence oil-immersed transformers are able to withstand the increased pressure surges encountered in large systems.

2. Every air-cooled transformer holds places which are not completely filled by the insulating material (frequently a compound) and hence contains air; for electrical reasons these places should not be present. Air contained in the layers of the insulation and between the insulation and the atmosphere has an effect similar to irregularities in the material itself. As a result of the difference of the dielectric constants ($\varepsilon = 2$ approximately for insulating material, and $\varepsilon = 1$ for air), the air is strained to such an extent that corona effects may result. Compounds which form nitric acid and ozone may be produced. Both of these substances attack the insulating materials (except glass and porcelain), and also the metallic parts. The nitric acid and the metal form conducting salts which are deposited on the insulation. When the process of decomposition has been carried sufficiently far, current is able to flow along the layer of salts and hence the insulating properties are destroyed.

3. Unless properly protected, air-cooled transformers are a continual source of danger to the attendants.

4. Air-cooled transformers are very sensitive to overloads. Owing to their small capacity for heat, they are unable to withstand large overloads for long periods as successfully as oil-immersed transformers. Excessive pressures lead to increased temperatures in the iron, and in some types also in the windings; hence there is a considerable danger that a defect in the transformer may be the direct cause of a fire.

5. Electrical stresses in the iron and copper must be kept comparatively small in air-cooled transformers, so that for outputs above 20 kVA approximately, these transformers, even with their disadvantages, are more costly than the reliable, oil-immersed transformers.

The unbounded practical possibilities for the application of such transformers for all cases that occur are obvious, and can only be fulfilled if the exacting conditions regarding the insulation and heating are satisfied; *these transformers, therefore, are essentially oil-immersed transformers.*

The manufacture of oil-immersed transformers necessitates extensive theoretical knowledge and practical experience. The disadvantages of air-cooled transformers are not entirely avoided in every oil-immersed transformer; probably defects in the construction or bad designs are the direct causes. In fact, even new difficulties, that would not arise with air-cooled transformers, may be introduced.

The oil filling, covering everything, tends to lead constructors, who are not sufficiently careful or conscientious, to make mistakes and thus discount the superiority which oil-immersed transformers have over those of the air-cooled type.

A series of oil-immersed transformers, made by Brown, Boveri & Co., is described in the following pages. This series is the outcome of considerable experience and development in recent years; *all theoretical and practical demands are fully complied with, thus the transformers are an absolutely modern and first-class production.*

BROWN BOVERI, THREE-PHASE, OIL-IMMERSED TRANSFORMERS

for outputs to 160 kVA and pressures to 20,000 V.

Transformers for outputs up to 160 kVA and high-tensions of 20,000 V are chiefly used in substations, where the primary side is at a high pressure and the secondary side at a low pressure. This kind of transformer is in service almost without interruption, as they are used as distribution transformers for the system and as sources of energy for villages; the load varies considerably. These transformers must, therefore, have such properties as will render them suitable for the changes in service. The mechanical and electrical reliability of these transformers must be unquestionable, they must need practically no maintenance, the initial and running costs must be small, and the cost of the energy losses occurring through changes in the load must be negligible.

Each of these conditions represents a series of involved problems and, for the greater part, one affects the other. In the present article it is impossible to give a complete description of the complex of questions which were encountered before the new series of transformers was evolved.

MECHANICAL PARTICULARS

1. Oil tanks.

All dimensions of the oil tanks of Brown Boveri transformers have been influenced by the attempt to keep the size as small as possible. The design of the oil tank is simple and the tank itself extremely suitable for the work. Welding of an excellent quality ensures perfect protection against oil leakage. Even with the small dimensions and small weight of the oil filling the rise in temperature of the oil is kept to within the usual limits. A respirator is provided in the cover in order to prevent water condensing in the interior of the tank; water is the cause of many defects.

Transformers with oil conservators are not constructed for these outputs. Actual experiences have shown that this type of transformer behaves as reliably in service as those with which a conservator is provided.

2. Windings.

The new series of transformers is exclusively fitted with concentric windings. The low-pressure winding is placed coaxially on the iron core, from which it is carefully insulated (Fig. 1). The high-tension winding is also coaxial and mounted above an insulating tube, which covers the low-tension winding and the intervening connections. The insulation used to separate the high-tension winding from the yoke and from the low-tension winding is of excellent quality. This construction enables either winding to be repaired when necessary. Single coils may be renewed or repaired in the high-tension winding also; this, on account of the small cost involved, is an advantage of considerable importance. This type of transformer is, of course, more costly to build than the types in which the windings are not separable. Experience and extensive special tests have shown that higher demands than have been usual for the past few years, are now placed upon windings for small outputs. The following are the chief modern requirements:—

(a) Great mechanical strength.
(b) Rise in temperature constrained to definite limits.
(c) The internal insulation to be of great strength.
(d) The external insulation to be of great strength.
(e) The windings to be protected from chemical actions.

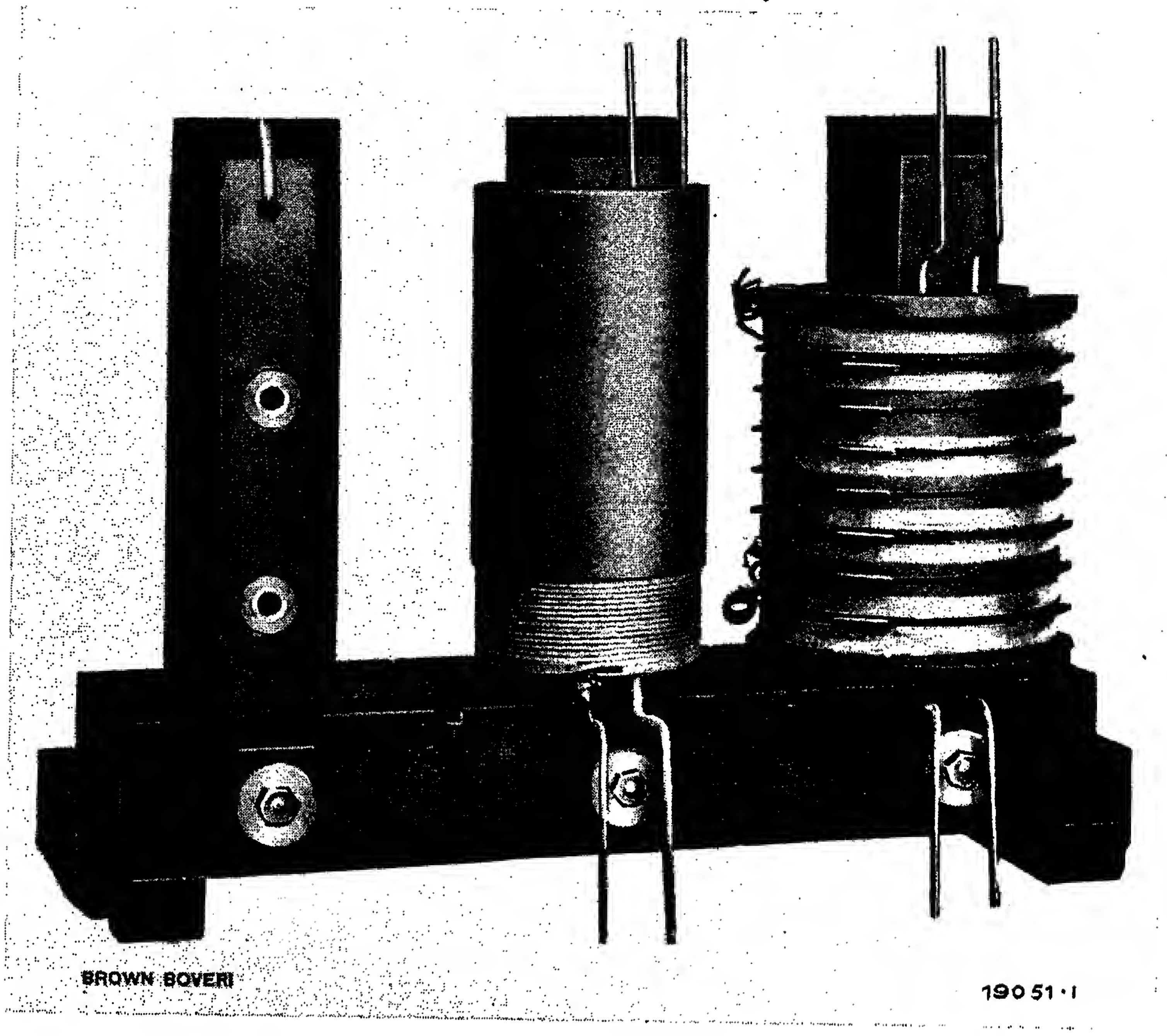


Fig. 1. — 30-kVA transformer, 10,000/400 V, Y/z connected, 50 cycles, during assembly.

The framework is assembled so that windings may be fitted.

The left-hand limb, still without the winding, enables the cruciform section to be seen.

The middle limb has the low-tension winding already in place, and the tube of insulation is partly in position. The winding and tube are of circular section.

The right-hand limb is shown with the high-tension winding, consisting of circular coils in place; it will be noticed that the winding is composed of individual coils. This design permits the coils to be replaced or interchanged with the minimum disturbance.

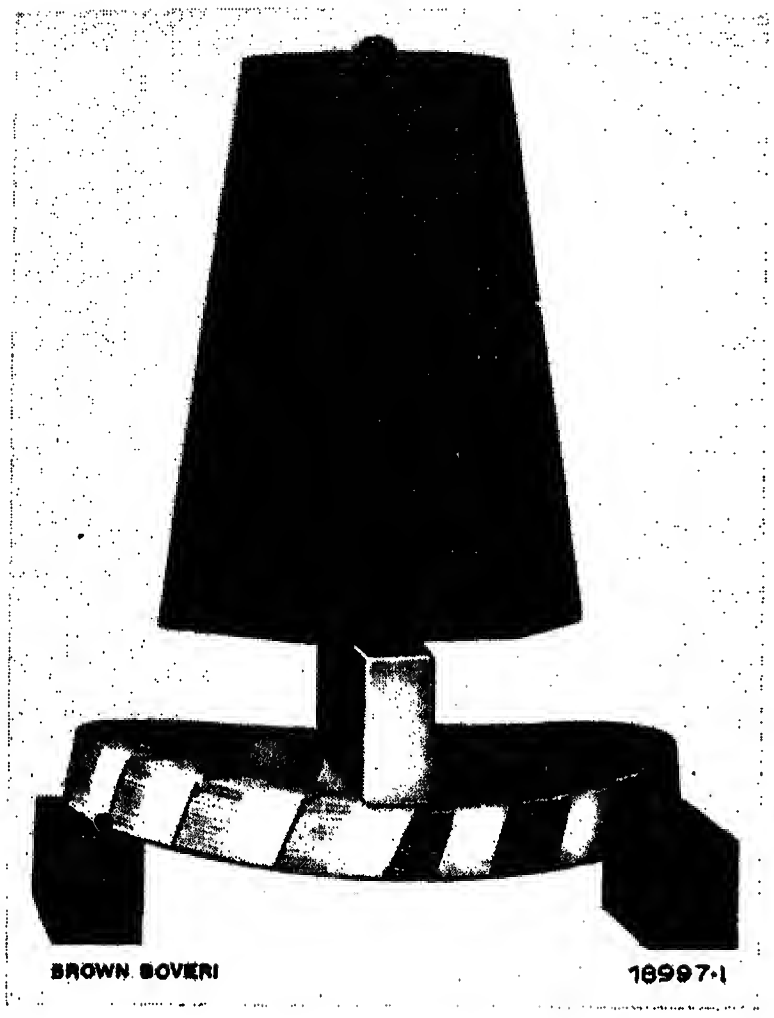
The transom of wood firmly secures the active part of the transformer to the feet in the tank.

Figs. 2 and 3. — Tests on the strength of round coils of various types.

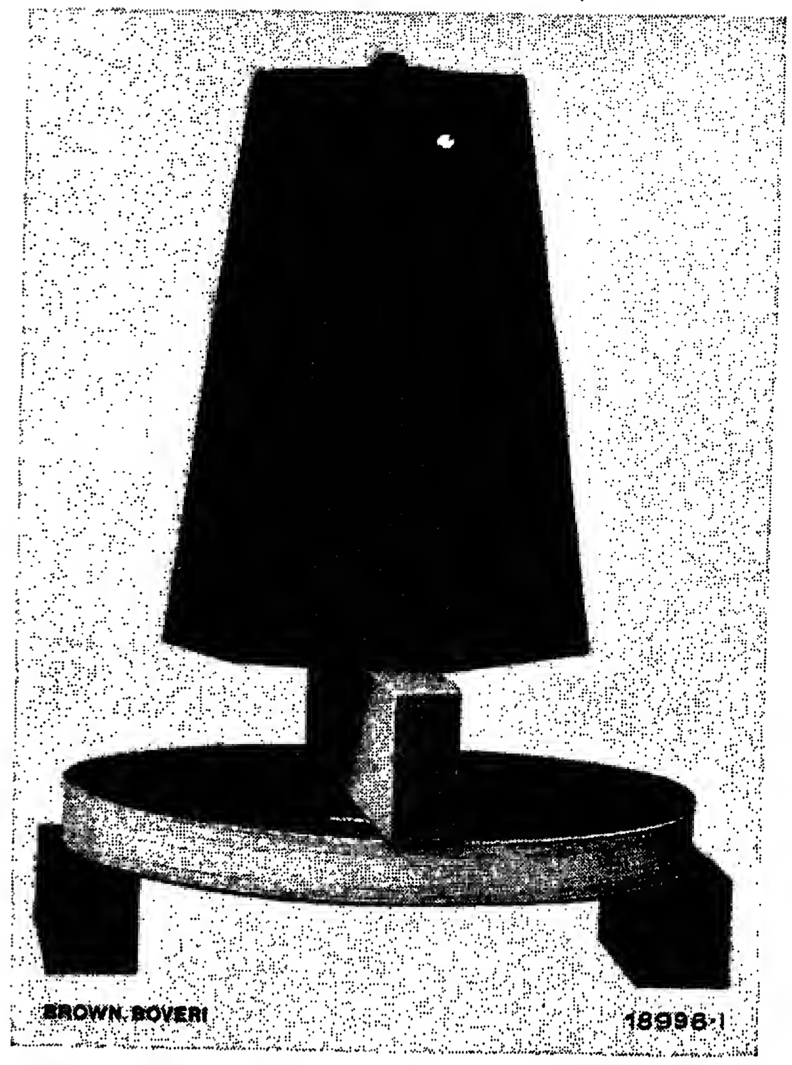
Left :—
Coil of the type generally used with binding.

Right :—
Coil of the special design, as made by Brown, Boveri & Co.

The illustration shows two circular coils each composed of 1·5 kg insulated wire, and having the same number of turns. Originally the coils had the same dimensions. The left-hand coil is constructed and bound in the usual manner, while that on the right-hand side has been wound according to the special Brown Boveri method. Both coils have been dropped vertically on to a hard surface, from a height of a metre. The coil on the left is completely deformed and of no further use, while the deformation of that on the right is so slight that it can only be detected by accurate measurement; the coil is as ready for service as one which has been carefully handled. This test shows the great mechanical strength of transformer coils made by Brown, Boveri & Co., and also ensures that the coils will resist the stresses arising in service.



Figs. 4 and 5. — Tests on the strength of round coils of various constructions.
Left :— Coil as in Fig. 2.
Right :— Coil as in Fig. 3.



The illustration shows coils similar to those described in Figs. 2 and 3, and of equal weights. They are each placed on two supports and carry a load of 15 kg mounted on a diametrical cross member. The usual type of coil on the left-hand side is considerably deflected, while on the right, the coil, constructed according to the Brown Boveri special design, is only deflected to an almost imperceptable degree.

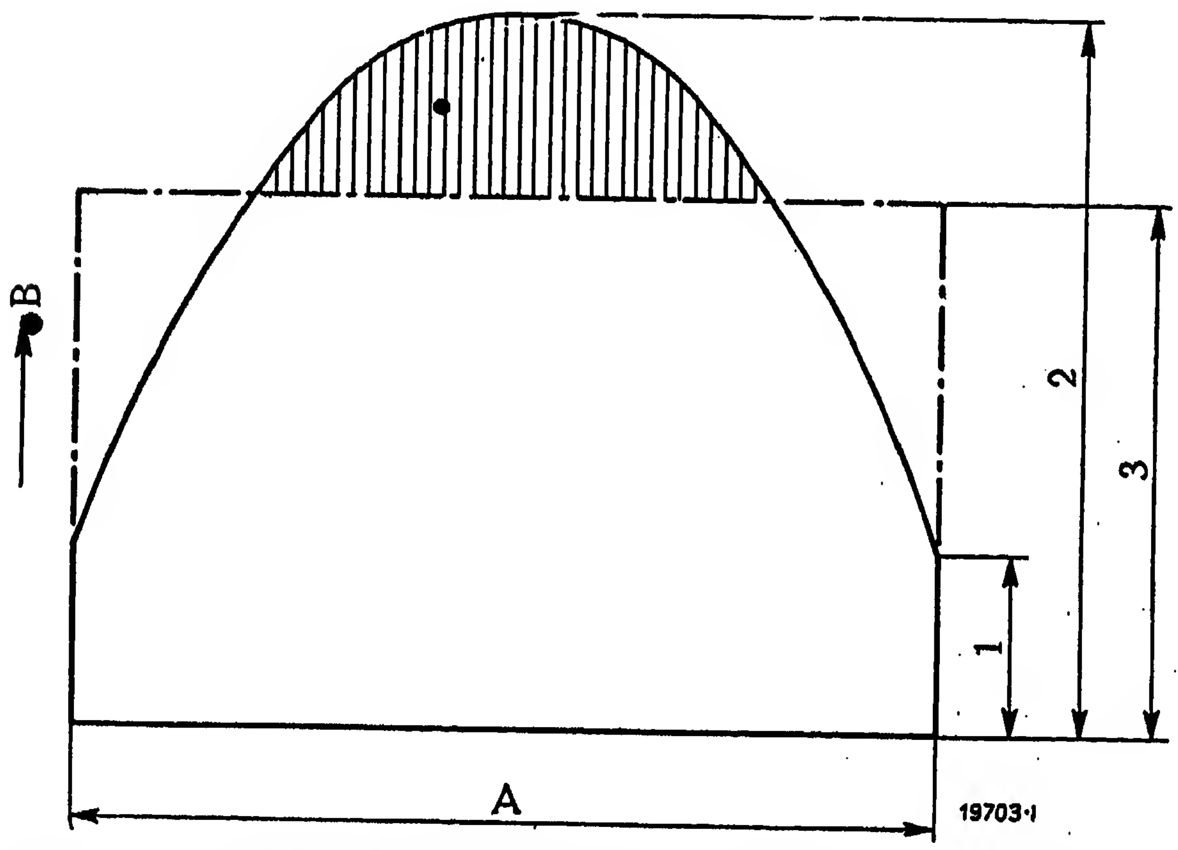


Fig. 6. — Temperature gradient in an incorrectly dimensioned coil.

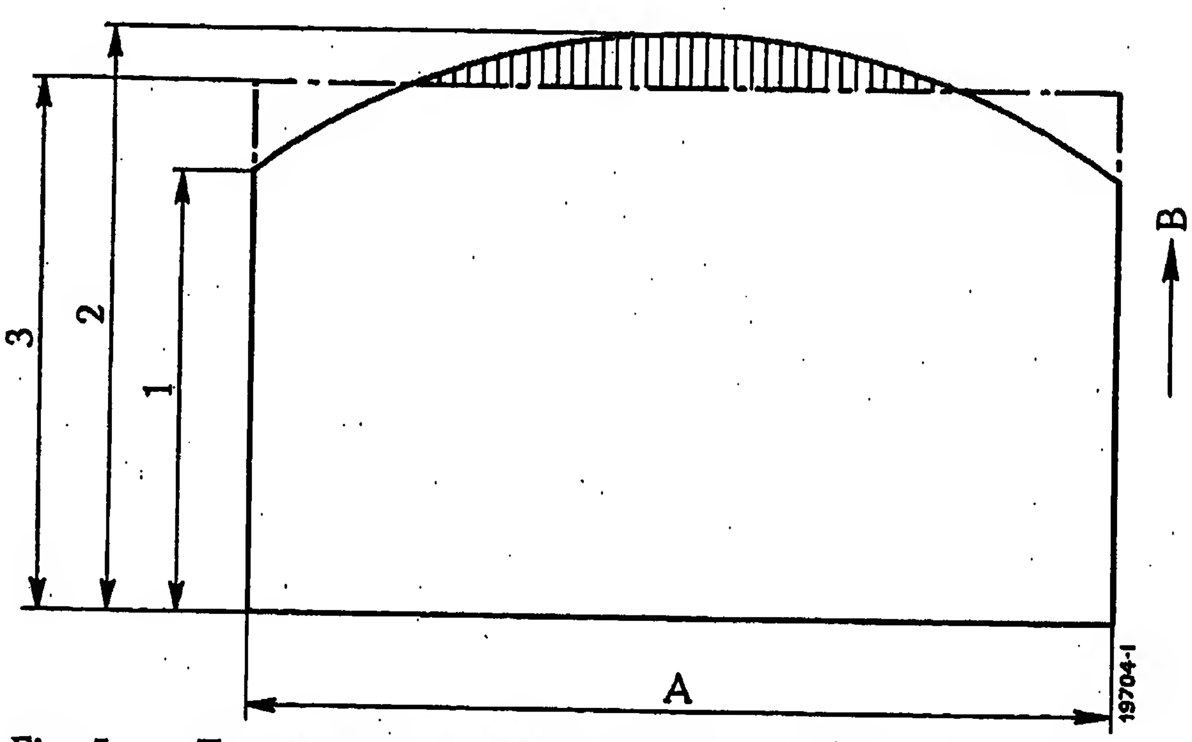


Fig. 7. — Temperature gradient in a correctly dimensioned coil.

A. Radial coil height.
B. Local temperatures along the radius of the coil.
1. Excess of temperature of the outside turns above that of cooling medium.
2. Maximum temperature of interior of coil above that of cooling medium.
3. Excess of mean temperature of coil above that of cooling medium.

The above curves show the temperatures at various places for two coils which have the same temperature rise, enabling comparison to be made with the temperature of the surrounding cooling medium. The ordinate 3, which is at the same height in each case, is obtained from the results of the test. It is possible to arrive at the erroneous conclusion that both coils have the same value. A winding is only permanent when no point in it is at a high temperature. The coil in Fig. 6 is unfavourable in this respect. The temperature of the outside turns of a coil forms no criterion for the behaviour of the inside layers. The small surface temperature shown by ordinate 1 compared with the mean temperature rise (ordinate 2) is an indication that inside the coil high temperatures are present. A good, permanent, thermic value for a coil is obtained if the maximum temperature only slightly exceeds the mean temperature.

The coils, used in small transformers made by Brown, Boveri & Co., are so dimensioned that the heating curve is similar to that in Fig. 7.

(a) Great mechanical strength. If a transformer is to be in continuous service, it must be fitted with coils which are mechanically strong. In coils, composed of many turns of thin wire, the individual turns must not alter their positions with regard to each other, through external or internal forces. This limit is fully attained in the small transformers made by Brown, Boveri & Co., by means of special measures adopted in the construction of the winding. The coils are both hard and strong and do not change their form in service (Figs. 2—5).

(b) Temperature rise between fixed limits. No point in the winding may attain a dangerous temperature. In spite of the relatively small current loading which must be used with transformers for small outputs, owing to the copper losses, all models placed on the market do not comply with these requirements. The high-tension winding which is composed of many turns, is particularly sensitive to the temperature rise. Coils formed by a large number of turns of thin wire have a large amount of insulating material and but little copper. The conduction of the heat from the inside of the coil is poor, because the conductivity of the insulation is about 3200 times less than that of the copper. Although the mean temperature of the coil may be only slightly above that of the surrounding oil, high temperatures may occur inside the coil if the heat has to traverse a long path before reaching the oil. Such transformers are very susceptible to heating and overloads. The interior of the coil may become charred, and a breakdown may soon result, owing to the unfavourable design of the winding. The usual heating tests do not enable such faults in design to be detected. *The small transformers, made by Brown, Boveri & Co., are suitably dimensioned and special care is paid to the cooling; hence overheating is unable to occur even with exceptionally high overloads* (Figs. 6—7).

(c) The internal insulation to be of great strength. It is well known that during switching operations, flashovers and *stray currents with steep wave fronts* are formed, especially during atmospheric discharges. Although only effective for a short period, these waves are able to stress the various parts of transformer windings to a great extent. After a very thorough investigation, Messrs. Brown, Boveri & Co. have determined the height of these waves, and the distribution of the stresses caused by them over the complete transformer winding. The results clearly showed the necessity for good insulation over the whole winding. For these reasons the complete length of the windings of Brown Boveri transformers, and not merely the commencing and finishing turns, as previously usual, is covered with insulation of excellent quality. Since 1922, surge tests have been included in the ordinary tests carried out on Brown Boveri transformers. All turns are tested by surges which are produced artificially and which stress each turn; the stress upon the winding depends on the steep front of the wave, which is equal to 1·3 times the working pressure of the transformer. The surge test ensures that only those transformers which will be able to withstand the large electrical stresses occurring in practice, shall leave the workshops.

(d) The external insulation to be of great strength. New tests on dielectric strength carried out by Brown, Boveri & Co., have supported the theories previously established by careful research. The results obtained confirm the correctness of methods of insulation previously used. Among other things, the use of insulating tubes made from good quality material, offers the best protection from flashovers between the windings, and has been employed by Brown, Boveri & Co. for many years. The special method of insulating the yoke from high-tension, as used for a long time by Brown, Boveri & Co., has also given excellent results. These systems are retained in the construction of the new series of transformers. For example, a pressure of 75,000 V must be attained before a flashover will occur between the windings and the yoke of a 20,000-V transformer.

(e) The protection of the windings from chemical influences. Modern research has shown that the destruction of the insulation of the windings, as occasionally observed, may be traced to the action of asphaltic acids which result from the oxidation of the transformer oil. Owing to the good work of their chemists and physicists, Brown, Boveri & Co. have at last succeeded in finding a means of impregnating the windings from this attack and also of rendering them immune from the absorption of damp (Figs. 9, 10 and 11).

3. Oil. A transformer can only work correctly over a long period if its oil-filling possesses the required properties. Unsuitable oil decomposes and forms sludge which is deposited between the windings of the transformer and also inside the tank, thus hindering the dispersion of the heat. As time increases the transformer will gradually become hotter even under constant loading conditions, and will finally be damaged unless a remedy is effected at the correct time. Brown, Boveri & Co. use only oil which has been tested for its general qualities, as well as for its stability when heated, for filling their transformers.

4. Tappings. The greatest percentage of all small transformers are provided with tappings which make them suitable for supplying the various points of consumption in a network or for changes in the loading conditions. The tappings are mounted on the high-tension side, almost without exception, as electrical reasons make it practically impossible to obtain the desired pressure accurately if the tappings are mounted on the low-tension side. The covers of transformers made by Brown, Boveri & Co. for pressures up to 11,000 V are fitted with special high-tension bushings which enable the change-over from one pressure step to another to take place quickly, reliably and easily. The pressure is changed by altering the terminals for those which correspond to the new pressure. With three-phase transformers connected in ⅄ and for higher pressures, the tappings are led to a switch immersed in the oil in the transformer tank. When not under pressure, the switch can be tripped, without breaking the connections, by turning a handwheel mounted above the cover. Similar to the transformer, this switch is also insulated for the full test-pressure.

Occasionally very complicated special constructions are required as well as the usual simple connections. These cannot be carried out with the two designs mentioned above, viz., tapping terminals or tapping switch. In such instances the change-over has to be performed with the active portion of the transformer lifted out. Complicated connections tend to give rise to mistakes in attendance and should therefore be avoided.

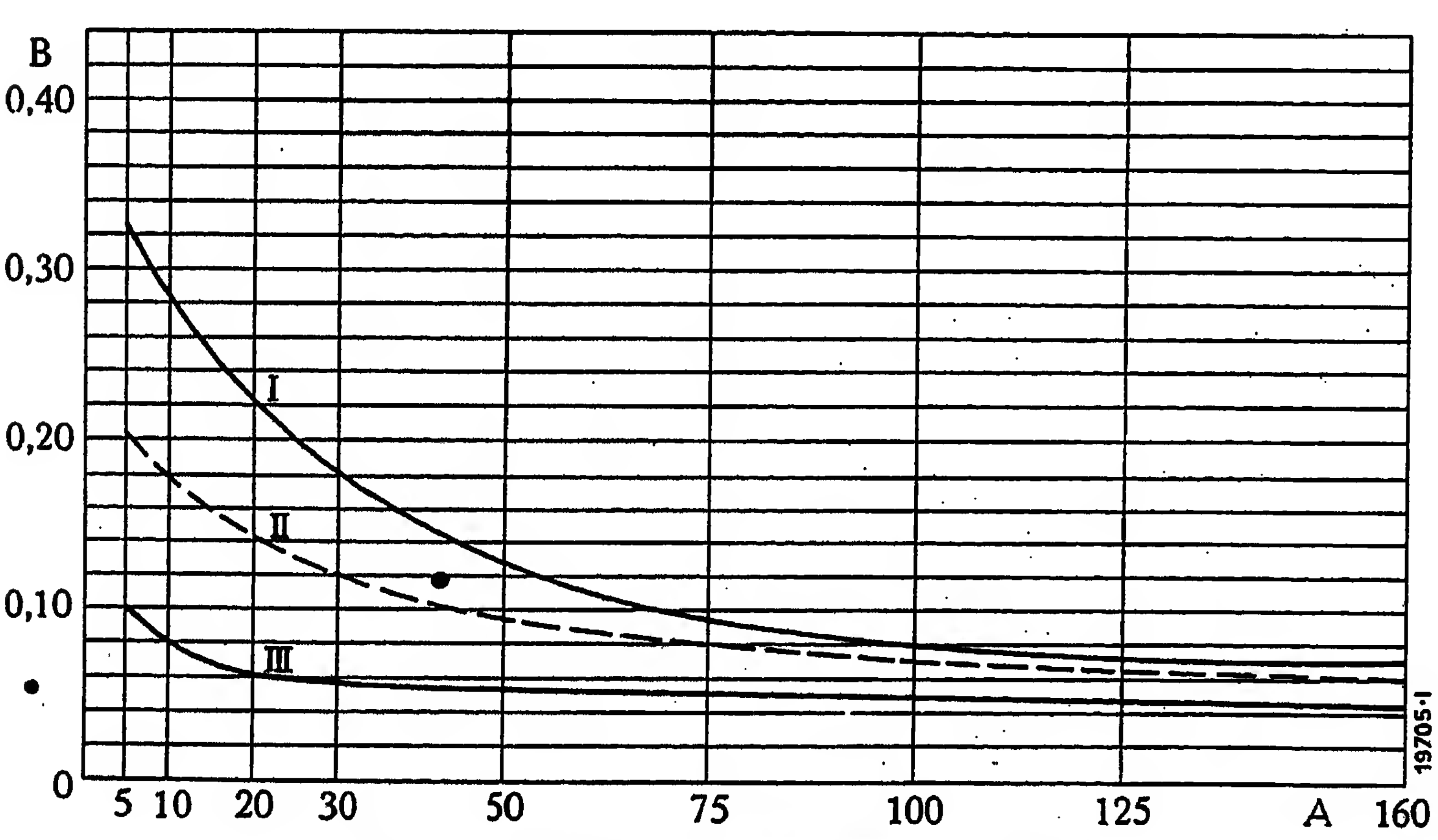


Fig. 8. — Ratio of no-load wattless kVA to nominal output of transformer in kVA as a function of transformer output in kVA.

Curve I, for transformers with butt-jointed cores. Commercial type made till about 1914.
Curve II, assumed curve for transformers with butt-jointed cores of modern construction.
Curve III, for Brown Boveri transformers with interleaved iron cores, for high-tensions of 10,000 V.

ELECTRICAL PARTICULARS

1. No-load current and no-load losses. Increased attention must be paid to the *no-load current* in a transformer owing to its economic effect upon the magnetic field which it maintains in the core. The no-load current particularly affects the power factor of the complete system. This large problem cannot be dealt with more fully in the present article, but it must be

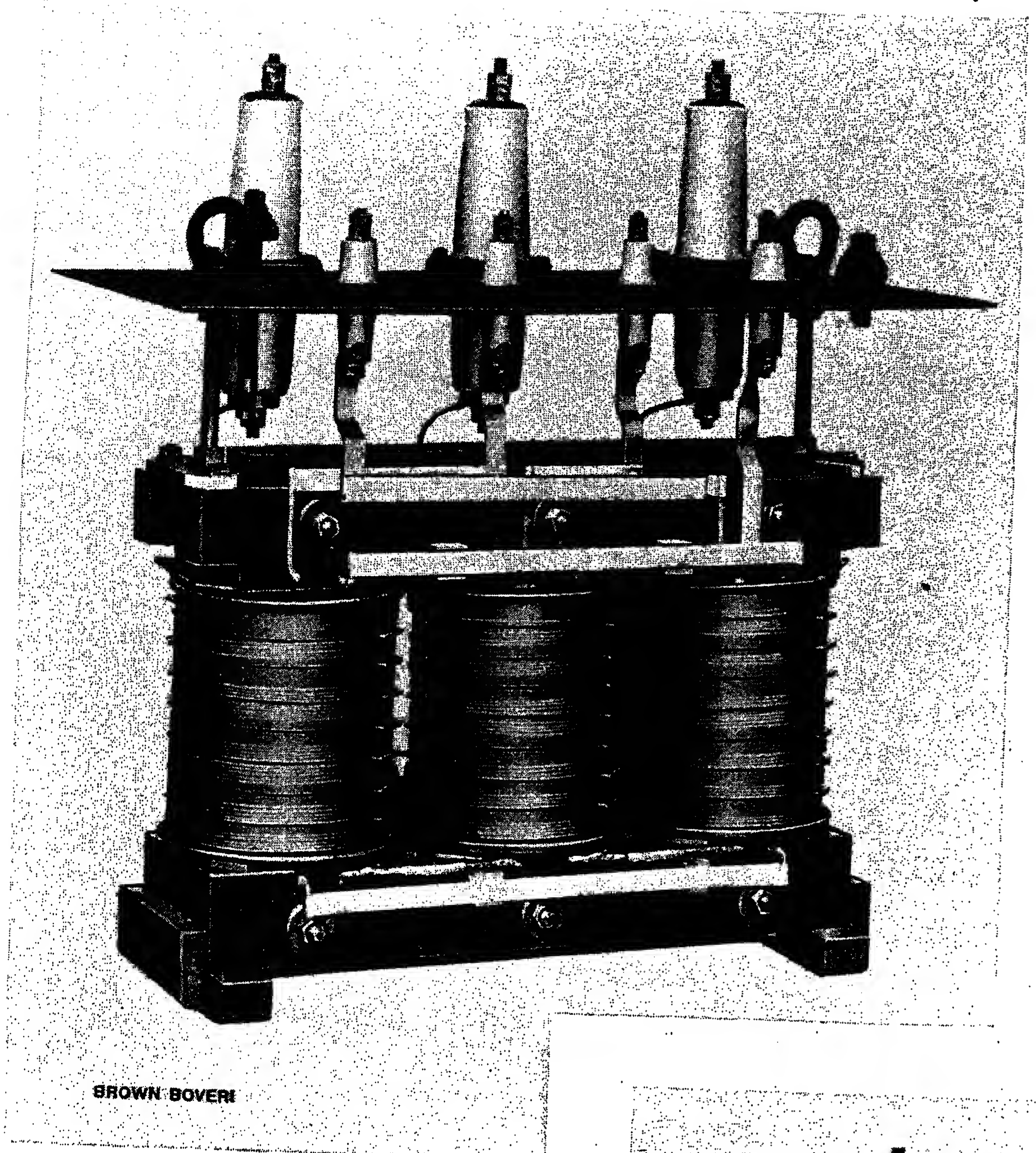


Fig. 9. — The active part of a 30-kVA transformer, 10,000/400 V, ⅄/Z connected, 50 cycles.

The active part of this transformer is finished and assembled, the windings are dried and lacquered. The windings are liberally dimensioned, and traversed by cooling ducts providing perfect cooling for all parts of the coil. In spite of the compact design the outgoing conductors are arranged in such a way that they can be easily supervised.

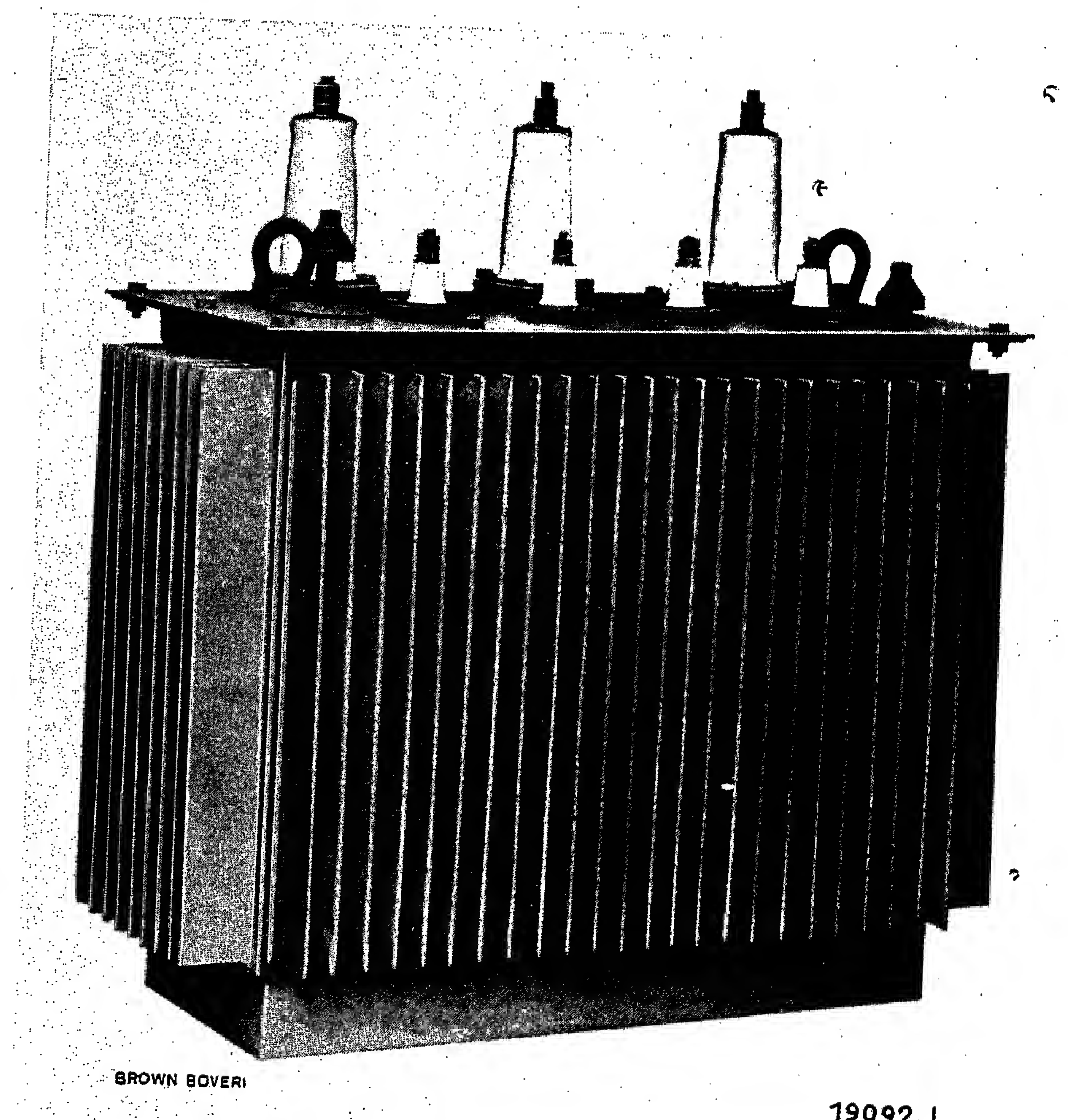
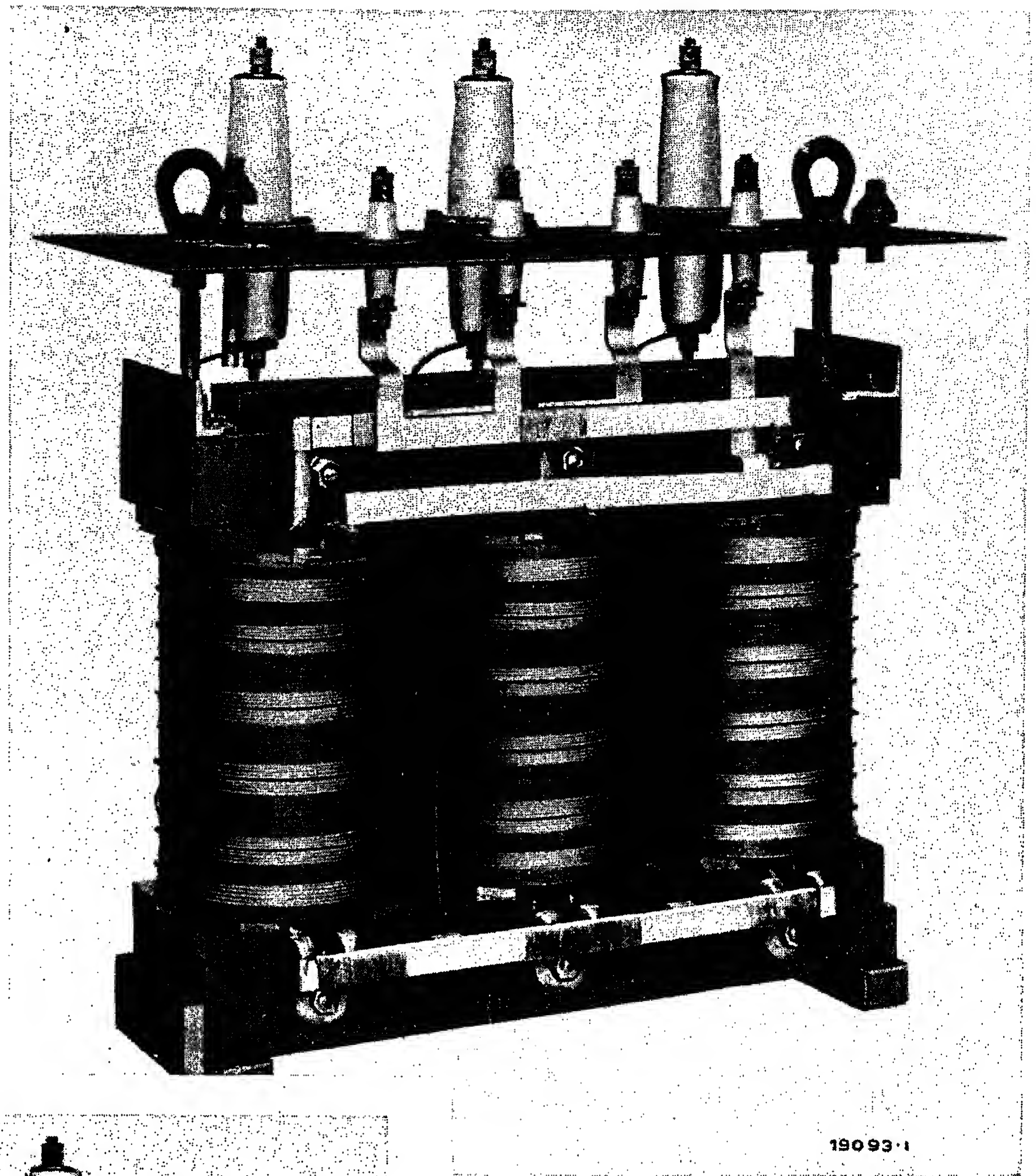


Fig. 10. — 30-kVA transformer, 10,000/400 V, ⅄/Z connected, 50 cycles, in tank.

The transformer is provided with its own tank, on the bottom of which the active parts rest. The lifting rings, visible on the cover, enable the active part to be lifted out directly. The transformer tank and oil filling may then be lifted by the cover.

Fig. 11. — 100-kVA transformer, 10,000/400 V, Y/Z connected, 50 cycles.

The details of construction are similar to those of the transformer in Fig. 9.



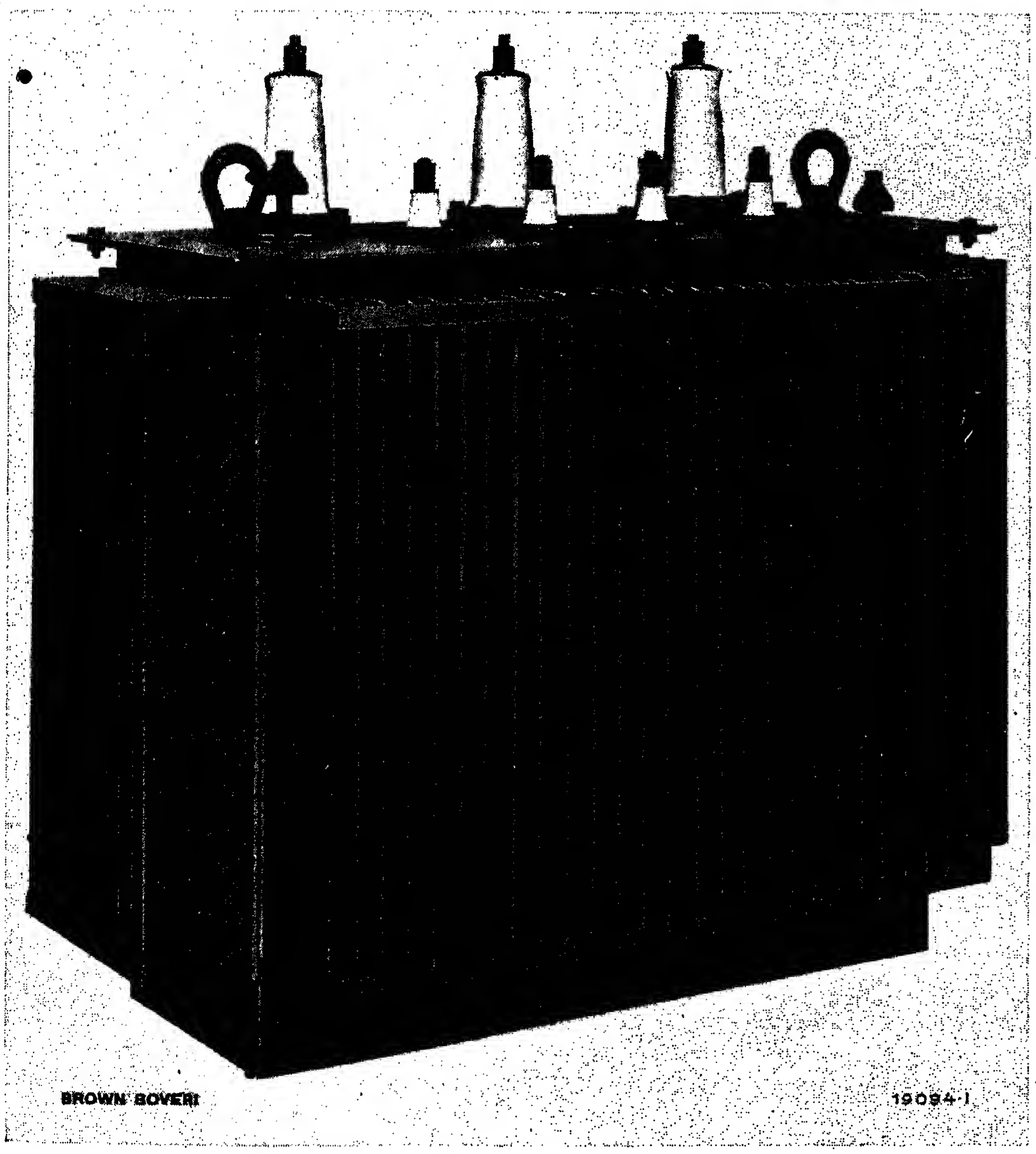


Fig. 12. — 100-kVA transformer, as above for 10,000/400 V, Y/Z connected, with tank.

mentioned that large sums are lost annually through bad power factors. The consumer of electrical energy naturally has to assist to bear this loss, and has to pay for the power at a higher rate than if the power factor were good. The supply companies assist the consumers to improve the power factor, by means of the cost of current; hence the no-load current of a transformer is no longer a matter of indifference to the purchaser.

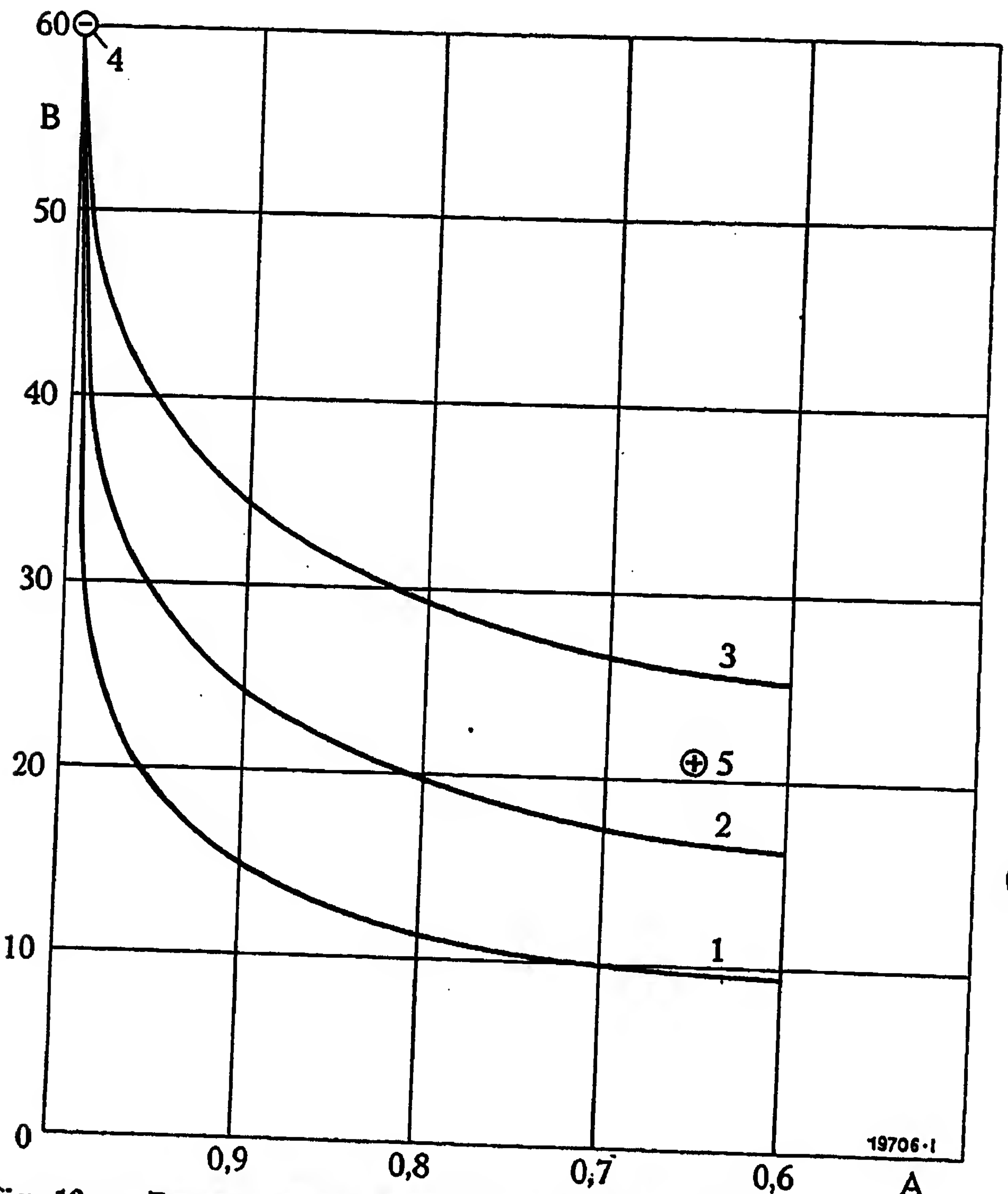


Fig. 13. — Percentage decrease of total wattless current of an existing distribution system by using transformers having particularly small no-load currents.

A. Power factor on secondary side of the distribution transformers.
B. Decrease in percentage of wattless current.
Curve 1. kVA × power factor. Peak loads for the system in question.
Curve 2. kVA × power factor. Half of the peak loads for the system in question.
Curve 3. kVA × power factor. Quarter of the peak loads for the system in question.
Point 4. For all loads and unity power factor and also for no-load.
Point 5. Mean annual value of the power factor on the secondary side of the distribution transformers.

Data of the system: 8000-V distribution pressure for agricultural and industrial purposes. Output of transformers installed, 1000 kVA, with individual transformer outputs of 10—100 kVA; about 1800 working hours per year. Diagram of distributing system as in Fig. 14.

For example, if the transformers installed in a system have a total calculated output of 1000 kVA (see Figs. 13—14), the use of small transformers made by Brown, Boveri & Co. offers an annual saving of 40,000 kWh, by reason of their particularly small no-load currents. The monetary value of the saving is 400 Francs per annum if the power costs one centime per kWh. The cost of energy is usually considerably greater than this; the figure of 1 centime/kWh is taken as a unit from which the charges may be reckoned proportionally.

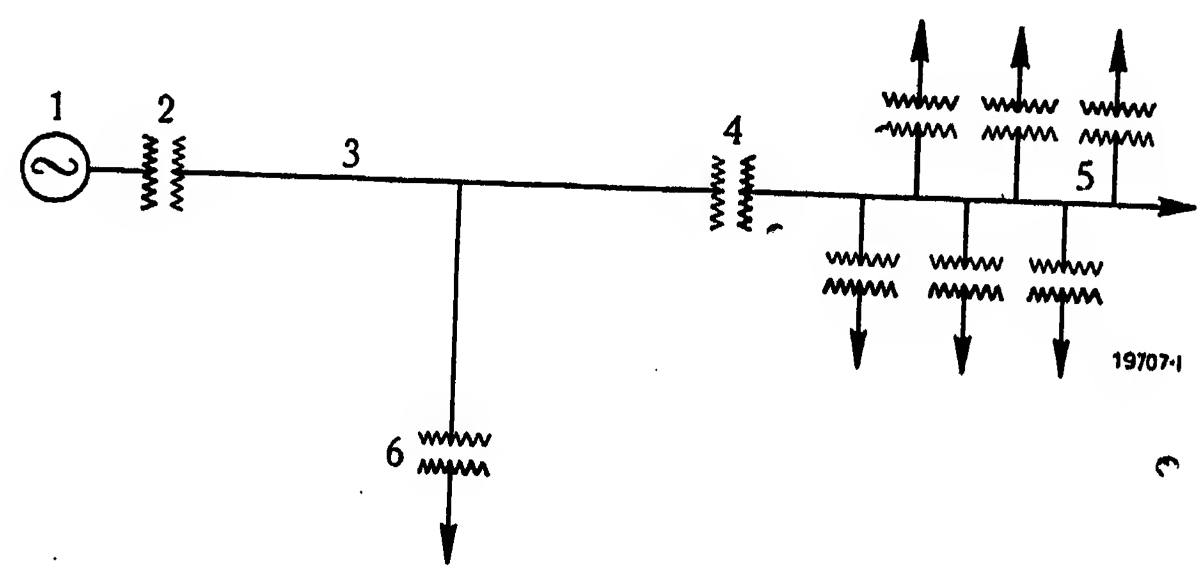


Fig. 14. — Diagrammatic distribution system.

1. Alternator wound for medium-high tensions.
2. Transformer stepping up the output to a high tension.
3. High-tension transmission line.
4. Transformer stepping pressure down to medium-high tension.
5. Distribution system with distribution transformer. The secondary side of the transformers is at a low pressure.
6. Step-down transformer for high-tension to medium-high tension. The system is not shown.

Fig. 8 shows the approximate percentage no-load currents of small transformers. The uppermost curve gives the approximate wattless current consumption of small transformers which have butt-jointed yokes, such as were on the market in 1914. The no-load current of modern transformers of this type may be a little more favourable, as shown by curve II. Curve III represents the no-load currents of transformers having interleaved iron cores. *The new series of small transformers made by Brown, Boveri & Co., have no-load currents which are still smaller than points on curve III.*

The no-load currents cause increased losses due to resistance in all conductors, even in the generator. The following particulars are applicable to the 8000-V system referred to (see Figs. 13 and 14).

If existing transformers, the no-load losses of which are represented by curve II in Fig. 8 (in reality the no-load losses are rather larger than these), are replaced by transformers the losses of which are shown by curve III, an annual saving of approximately 17,500 kWh is effected; with power costing 1 centime per kWh this has a monetary value of at least 175 Francs and other economies are also effected.

As well as the saving of 17,500 kWh, previously mentioned, there are reduced losses to the extent of about 6000 kWh in the step-down transformer, 14,000 kWh in the high-tension system and about 2500 kWh in the step-up transformer, or a total of 40,000 kWh per annum. If energy costs 1 centime per kWh, each transformer thus effects a saving of 400 Francs per year. In the value chosen for the high-tension supply and step-up transformer it must be remembered that energy is supplied also by other systems, whereby the size of the complete plant is affected. The saving is, however, only due to the influence of the small wattless power of a 1000-kVA distribution system. These values, although entirely neglecting the influence on the alternators, show the economic advantages of using transformers having small no-load currents, such as those constructed by Brown, Boveri & Co.

The no-load losses are, in the first place, of considerable importance to the user of the transformer. Apart from the less frequent cases, in which the transformer is disconnected from the supply mains when on no-load, the no-load losses are a source of expense during the complete life of the transformer. With power costing 1 centime per kWh, a continuous loss of 1 kilowatt causes an outlay of 87·6 Francs per year; estimating the life of a transformer as 15 years and assuming a rate of interest of 5 % this represents 1887 Francs.

The expense involved by losses forms a considerable percentage of the initial cost of the transformer, and must be taken into account when estimating the value of a design. The result of calculations of this kind shows that 100 watts saved on the no-load losses, justifies an additional initial cost of about 90 Francs.

Owing to suitable dimensions, the new type of Brown Boveri transformer has small iron losses as well as small no-load currents. These advantages can only be obtained by the use of an interleaved core, the iron losses in this type being about 10 % smaller than those in butt-jointed transformers.

In spite of the great economical advantages possessed by transformers having interleaved cores, occasionally an adverse prejudice is encountered.

The somewhat shorter time required for the assembly of iron cores of the butt-jointed type, after having been dismantled for alteration or repair, is often unfairly used as an advantage over the more economical interleaved type of transformer. Such a point of view would only be justifiable if the number of transformers in constant service were small when compared with the number undergoing alteration. Brown Boveri transformers for small and medium outputs, however, have shown that they can remain in service for years without being opened, either for repairs or alteration.

The new Brown Boveri transformers are fitted with windings of such good electrical properties that repairs are hardly ever necessary.

It is unreasonable to design all small transformers with butt-jointed cores, having large iron losses and no-load currents, in preference to transformers with interleaved cores, merely to shorten the dismantling and erection times by about an hour for some of the transformers, which form a very small percentage of the total number.

Butt-jointed cores are obsolete for small transformers on account of their failing in economy. Brown, Boveri & Co. discontinued the use of such transformers, for medium and low-pressures, more than ten years ago.

2. Copper losses. These are kept within certain limits, which, in conjunction with the exceptionally low no-load losses, give a particularly high efficiency that is retained even at partial loads. The maximum efficiency with these transformers is obtained when working at about 60 % of the full-load.

It is not always appreciated that, in actual service, the copper losses of a transformer have a comparatively small effect on the annual efficiency, but this is not so with the iron losses. The value of the copper losses amounts to only about $^1/_{10}$ to $^1/_8$ of the total losses on full load. The daily diagrams of networks supplying factories show a mean output having a maximum value of 25—30 % of the apparent daily output of the installed transformers. Distribution systems supplying agricultural districts are loaded to a still smaller extent, see Bulletin de l'Association Suisse des Electriciens, 1924, No. 9, p. 433.

It will probably not be far wrong to apply the average result to the individual transformers. Owing to the load peaks, the average equivalent copper losses are rather higher than $0{\cdot}25^2$ to $0{\cdot}3^2$ but, in any case, do not exceed 10—12 % of the copper losses for the transformer on full load, thus showing that these losses have a very small influence upon the annual efficiency.

3. Parallel operation. The dimensions of Brown Boveri transformers are so chosen that the transformers are able to operate in parallel successfully. All transformers of this series, made for the same pressure ratio, may operate from the same busbars, if the ratio of the outputs does not exceed 1:5.

TRANSPORT AND ERECTION

Brown, Boveri & Co. generally despatch small transformers dried-out and filled with oil. After examination on site for short-circuits or breaks caused by transport, the transformers are ready for service. If a transformer is not put into service until after 14 days from the date of despatch, the oil should be tested for water content. In the event of the result of the test being satisfactory the transformer may be immediately taken into service, but if the oil is found to contain moisture, it must be dried out in a suitable manner before the transformer operates.

For transport overseas or to other places where difficulties are likely to arise, the transformers are carefully wedged in their tanks which are secured in strong packing cases. On arrival at the place of erection the packing cases and wedges must be removed. The transformers must then be examined and filled with dry transformer oil, and after testing they are ready for service.

Brown Boveri small transformers possess the following characteristics:—

Mechanical.

Simple design, small weight of oil, small dimensions, very strong windings built of individual sections, all parts easy to assemble or dismount.

Electrical.

Very small iron losses, exceptionally small no-load losses, greatest possible resistance against short-circuit. Excellent insulation between the windings and iron, as well as between the turns. Economical operation as a result of small copper losses. Favourable cooling conditions, no hot spots.

These transformers are probably the most nearly perfect available to-day, and they ensure economical service for all practical purposes. The workmanship and the materials used are of first-class quality and the transformers fully comply with all existing technical requirements.

Reprinted from
THE BROWN BOVERI REVIEW
published by BROWN, BOVERI & COMPANY, LIMITED, BADEN (Switzerland)

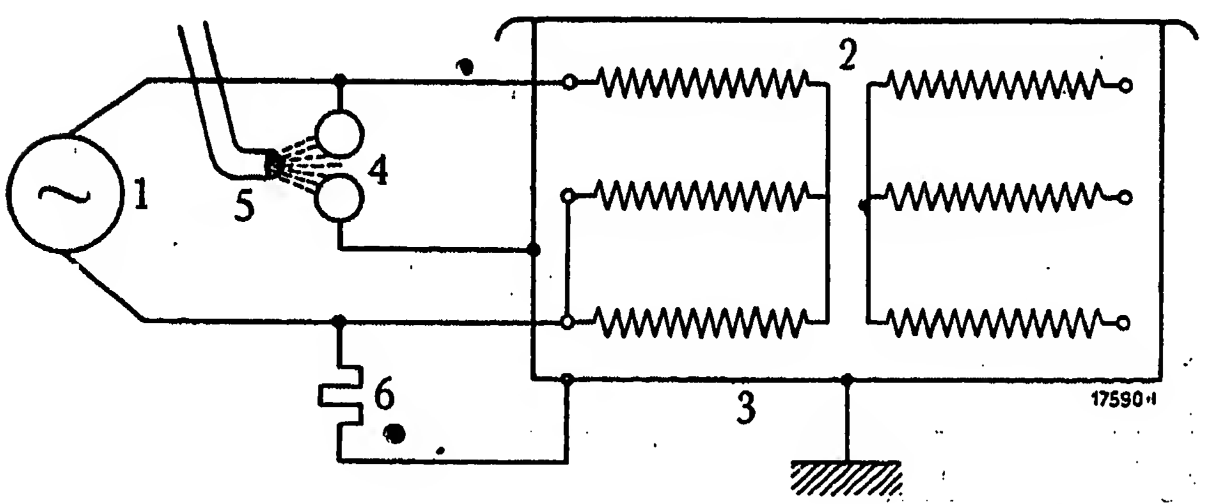
SURGE TESTS IN THE BROWN BOVERI TRANSFORMER DEPARTMENT.[1]

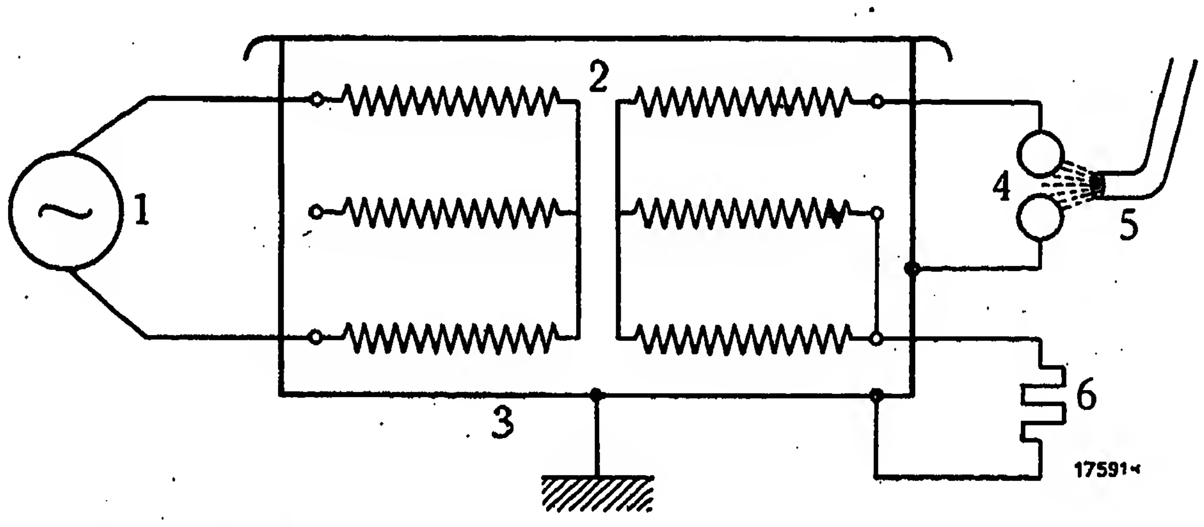
Decimal index 621. 314. 3.

UNDER actual working conditions, all transformers are subjected to surges which stress the insulation of neighbouring parts, such as coils, layers, and turns. Surge tests are carried out to examine the effect of stresses occurring in operation, and also to ensure that no manufacturing defects are present.

All transformers, to work with pressures greater than 3 kV (whether power or potential transformers), constructed by Brown, Boveri & Co. are submitted to surge tests before leaving the workshops. The connections of the circuit used for this purpose are the same as those published in the "Bulletin de l'Association Suisse des Electriciens" for August 1923 and are shown in Figs. 1a and 1b. Since January 1, 1924 this circuit has been recognised in Switzerland as the standard circuit for tests of this kind.

The surges occurring in practice are caused, almost exclusively, by flashovers to earth in the neighbourhood of the transformer. In the surge test, the actual conditions of a flashover should be reproduced as nearly as possible, if the test is to have any practical value. The surges are generated by charging the winding to be tested and suddenly discharging it to earth, which work is accomplished by a sphere spark gap connected between the terminal of the winding and earth. This terminal is charged by the induced voltage of the transformer until the spark gap breaks down. The spark which passes discharges the terminal suddenly, and a surge therefore results, the amplitude of which is that of the tension necessary to spark across the gap.





Figs. 1a and b. — Diagrams of connections for surge-testing apparatus.

1. Supply at frequency equal to or higher than that of the apparatus tested. The sources of supply can be protected from the influence of surges in various ways, e. g., condensers or choke coils.
2. Transformer to be tested.
3. Transformer tank.
4. Spark gap with compressed-air blast.
5. Compressed-air pipe.
6. Resistance.

The surge produced in this manner has very nearly the same effect on the internal insulation of the windings tested as a flashover when in service. By changing over the connections between the transformer terminals, the spark gap and the resistance 6 it is possible to test the insulation of each phase of the transformer successively.

To avoid the introduction of unknown quantities, as, for example, the earthing resistance, the spark gap is connected to earth and to the terminal of the transformer used, by connections as short as possible. The fulfilment of the preceeding conditions ensures that the flashover produced is such as would occur in service and that all transformers are tested in a uniform manner. Fig. 2 shows the stress set up in

[1] See The Brown Boveri Review, 1925, No. 3.

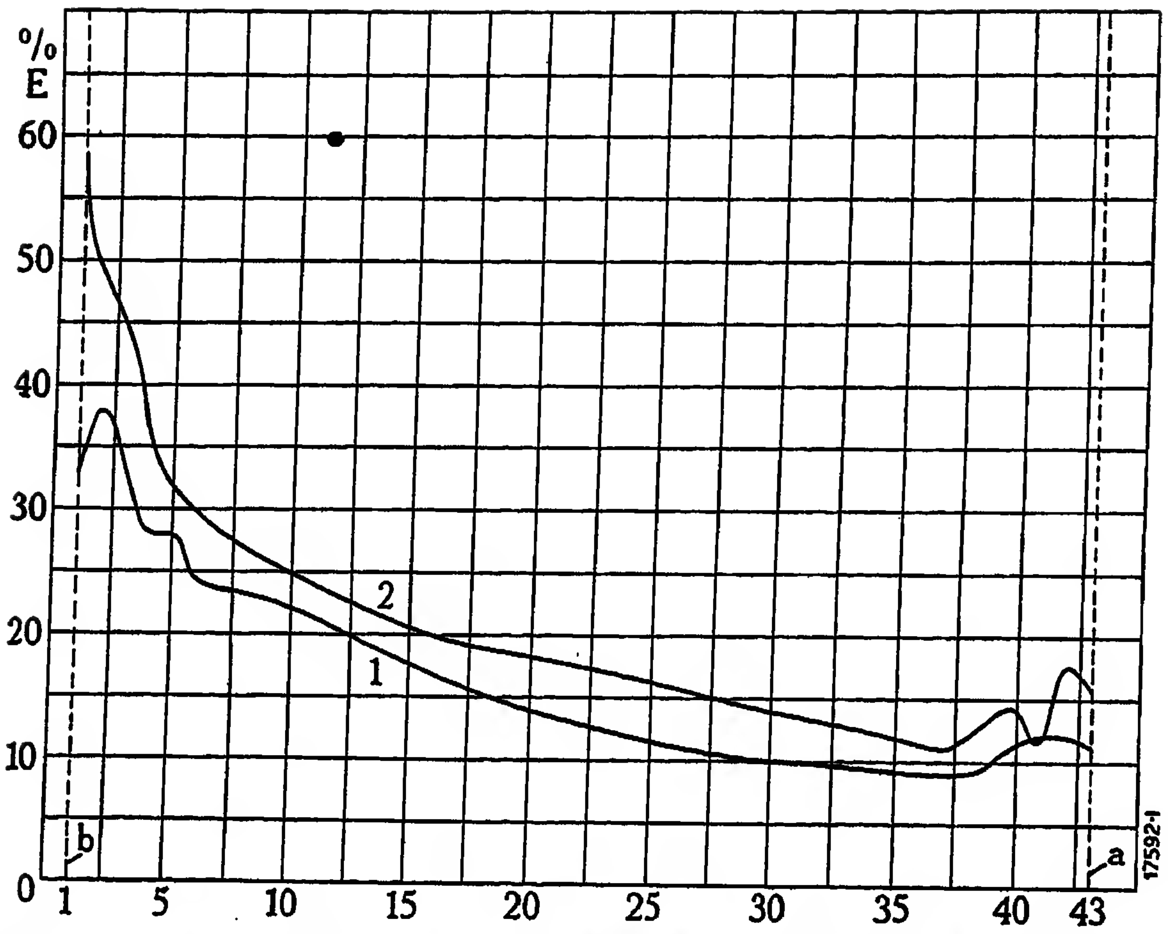
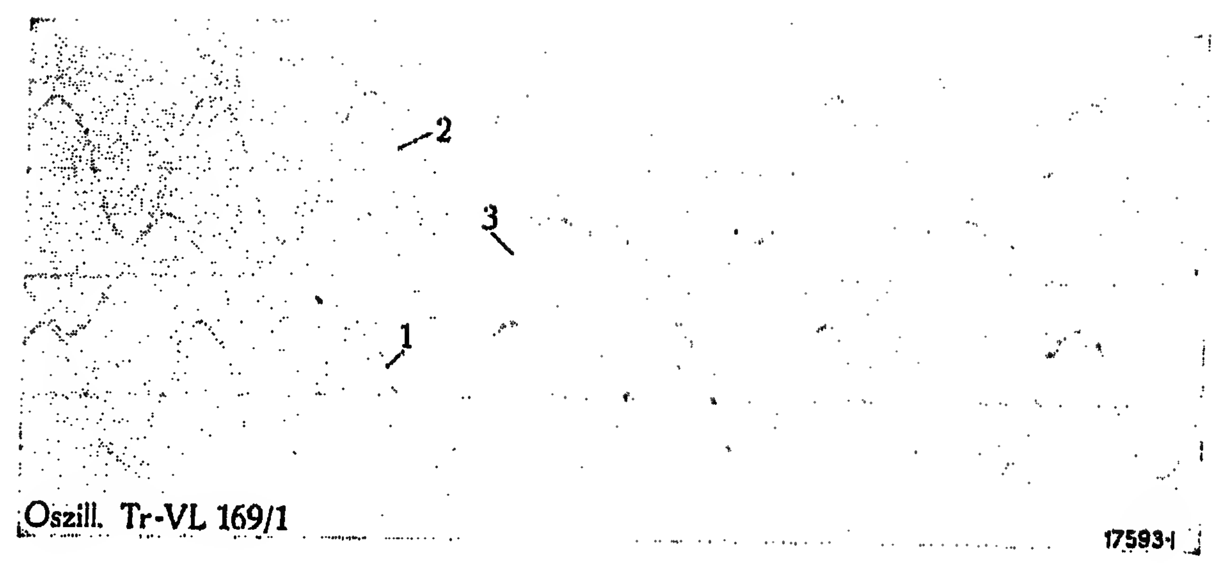
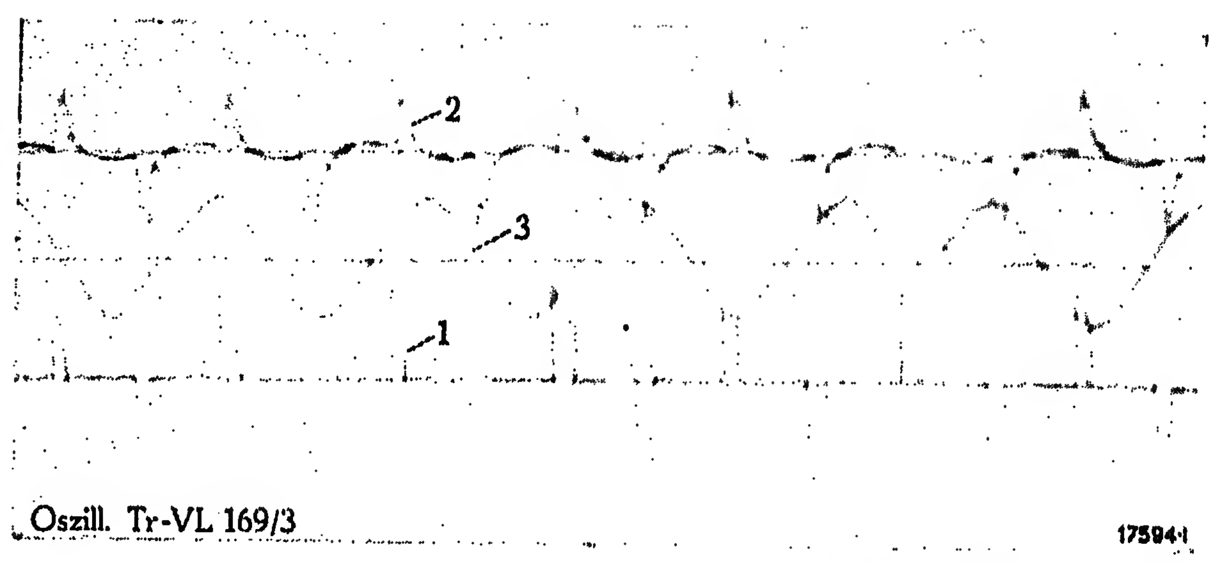


Fig. 2. — Distribution of stress in the coils of a transformer winding for 57 kV and 6000 kVA at 50 cycles. Influence of surge as a percentage of the amplitude of the surge E.

Curve 1. Terminal flashover of transformer.
Curve 2. Surge test.

a. Zero point of transformer.
b. Terminal.





Figs. 3a and b. — Oscillograms of a surge test.

Curve 1. Current in spark gap.
Curve 2. Pressure in resistance (6 in Fig. 1).
Curve 3. Time scale = 40 cycles.

a 6000-kVA transformer coil compared with that of a terminal flashover in actual work.

The spark taking place between the spheres is at once extinguished by means of a blower and occurs again in the succeeding half period, as shown in the oscillograms Figs. 3 a and 3 b which prove the correctness of this statement. The current across the spark gap when a blower is not in use is shown in Fig. 3 a, while in Fig. 3 b the effect of a blower on the current crossing the gap is shown. In the first case the current passes continuously in a similar manner to an alternating-current arc, while in the latter the initial values of both current and voltage are a maximum but immediately fall to zero.

The resistance 6 in Figs. 1 a and 1 b permits the potential of the terminal under test to be raised to that of the full voltage of the transformer to earth. This resistance must be at least 0·5 ohms per volt to prevent the current across the gap from becoming too large, and the greatest value shall be approximately 2 ohms per volt so that the excess

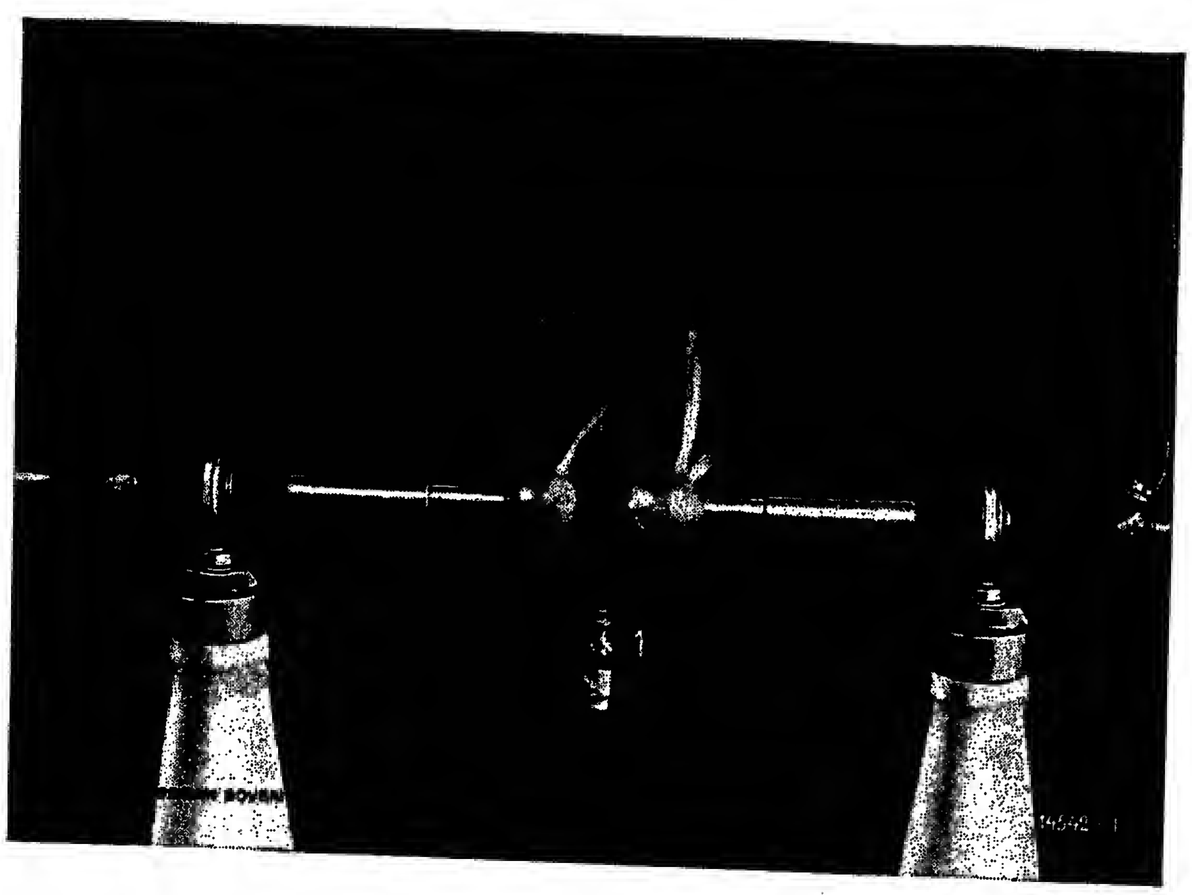


Fig. 4 a. — Flashover of the spark gap at 50 kV, without compressed-air blast.
1. Pipe for compressed air.

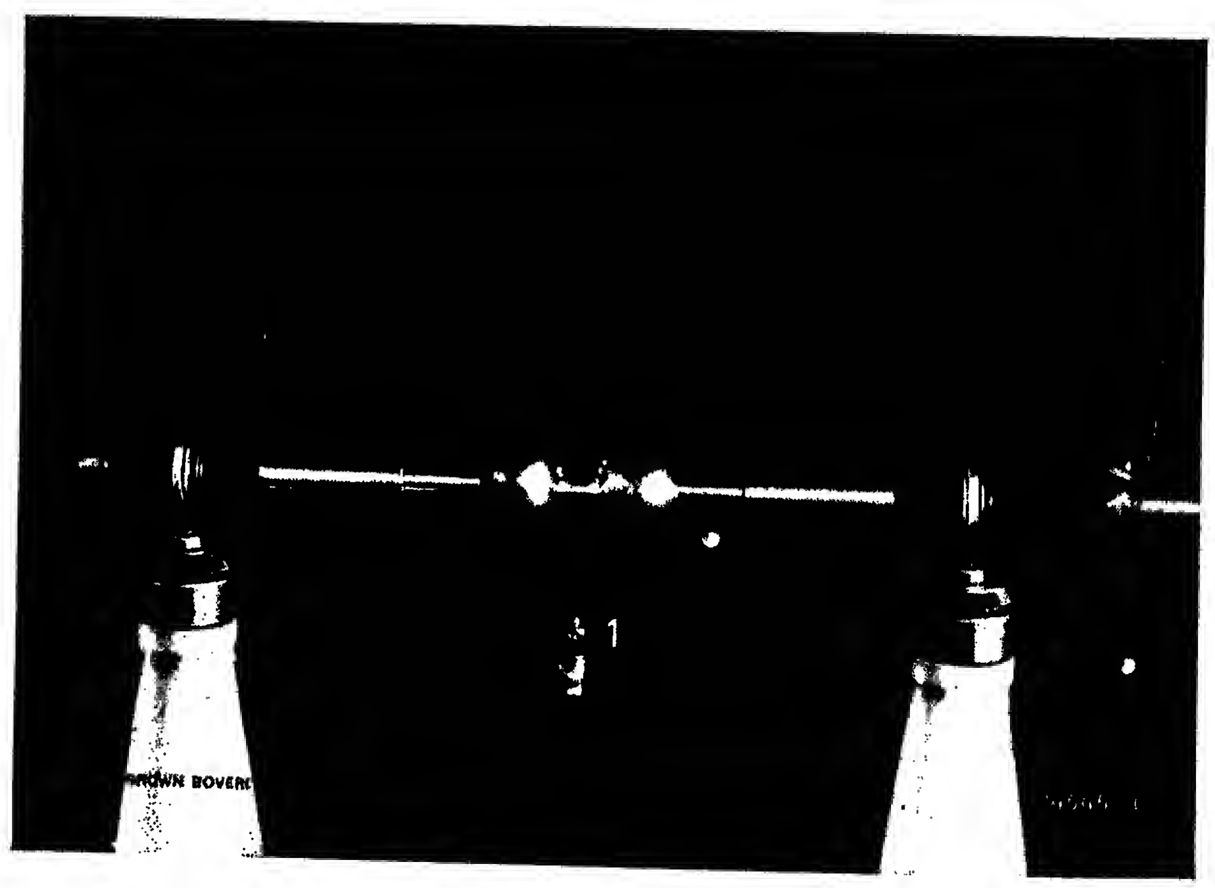


Fig. 4 b. — Flashover of the spark gap at 50 kV with compressed-air blast.
1. Pipe for compressed air.

When the blast is not in use the arc will be maintained, and, as a result of bad cooling it will be driven upwards. By good cooling, on the other hand, the blast breaks the arc before it has reached a great length.

SURGES AND THE RESULTING ELECTRICAL STRESSES IN TRANSFORMERS.

Decimal index 621.314.3

Introduction. Electromagnetic phenomena and their effects on the windings of electric machines and apparatus, particularly of transformers, have been the object of exhaustive investigation for a number of years. But, as shown by the publications which have hitherto appeared on the subject, it is extremely difficult to obtain exact results by theoretical treatment alone. The attempts made to obtain by direct measurement some information as to the electrical stresses set up in transformers by surges may, therefore, prove of interest.

The great practical importance of these phenomena is indicated by the fact that the majority of transformer failures are, to-day, the result of surges and the comparatively frequent breakdowns between coils and individual layers can only be attributable to this cause. This indicates that, with many types that have hitherto been on the market, the arrangement of the windings and the insulation of the coils are inadequate to withstand such electrical stresses. It is necessary, therefore, to ascertain the nature and extent of the stresses arising from this cause, as this is the only way in which it is possible to take account of their influence in the development of new designs.

Brown, Boveri & Co. have carried out tests on a large transformer, measurements being made with the object of obtaining useful data on this question. For this purpose, a transmission line 11 km in length was placed at their disposal by the North East Switzerland Supply Co.

The purpose of this brochure is to make known the results of these tests and to indicate certain conclusions which may be derived from them.

I. THE ORIGIN OF SURGES.[1]

Surges are a special form of travelling wave with a steep front; they originate at points where constant working conditions are disturbed by a sudden change in current and pressure. Among the causes of these changes, may be mentioned: arcing grounds, lightning disturbances both direct and indirect, switching in and out, etc. Experience shows that the dangerous travelling waves are those which originate in arcing grounds, especially as the result of indirect lightning disturbance; these are the true steep-fronted surges.

Travelling waves are either charging or discharging; their origin and properties are briefly considered below.

(a) **Discharging waves.** If a conductor is under a pressure E with regard to earth, it carries a certain charge in consequence. Should the point A (Fig. 1) become suddenly grounded, the potential to earth

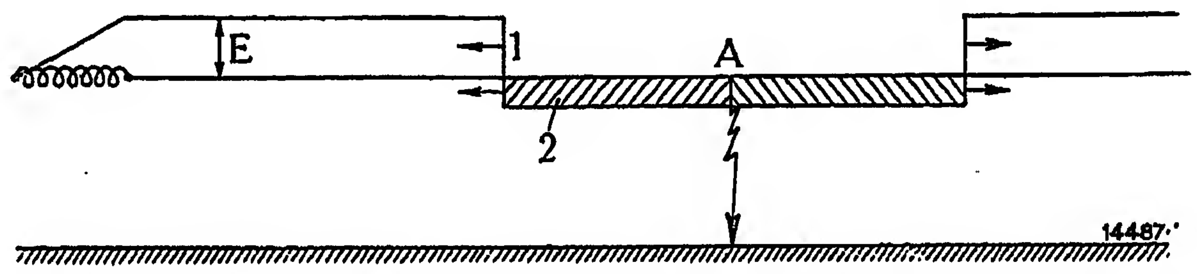


Fig. 1. — The generation of travelling waves due to grounding.
1. Pressure wave.
2. Current wave.

at this point falls to zero, with the result that the charge at A is liberated and flows away to earth. This falling of the pressure to zero at one point is immediately followed by a similar effect at neighbouring points on the line, progressing outwards in both directions. The charge is correspondingly liberated, and flows away to earth over the point of grounding; i. e., between the two points where the pressure breaks down and the ground, a current flows continuously.

The advancing break-down of the potential of the conductor to earth is known as a discharging pressure wave, and that part of it at which the pressure falls from the value E to zero is called the wave front. If the latter only extends over a short length of the conductor it is known as a steep front[1] and the wave itself as a surge.

By "discharging current wave" is meant the advance along the conductor of the point from which

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[1] This subject receives more accurate treatment in the appendix § V.

See also Bulletin de l'Association Suisse des Electriciens, 1922, No. 10.

[1] As the wave front is travelling, this can be stated equally well:—If only a short time is required for the value of the pressure at a point in the line to drop from E to zero, the wave is steep-fronted.

the charge is flowing away; this spreads simultaneously with the discharging pressure wave.

In the case of overhead transmission, travelling waves move with the velocity of light and with cables somewhat slower.

The relation between the amplitude of the pressure wave (the pressure peak E) and that of the current wave (the value of the current at the wave front) is called the wave resistance of the conductor. This is given approximately by the expression $\sqrt{\frac{L}{C}}$ where L is the inductance of the conductor and C its capacity, both per unit length and with reference to earth. As long as these values can be considered constant, the wave resistance is a constant for the conductor. The reflection effect is also of importance in the stressing of windings by travelling waves. For instance, should the discharging wave reach an open end of the line, the section of line in question is thus free from pressure; at this instant, however, a current flows throughout its length. As soon as the last of the charge flows away towards the grounding point, the current becomes zero, commencing at the end and progressing along the conductor. As each portion of the line has a definite inductance, a potential to earth is again established as the current falls to zero, its magnitude conforming with the ordinary laws of induction. The variation in the current now progresses in the reverse direction to that of its origin (the flow of the current wave outwards from A), hence the resulting pressure must be of opposite sign to that of the outward-moving discharge wave. The relationship between the disappearing current wave and the new pressure wave is again that given by the wave resistance of the line; the amplitude of the latter is thus theoretically equal to E. When this inward-flowing pressure wave arrives at the point A, the whole portion of line under consideration is at the potential —E to earth; at the ground itself it falls to zero and a new discharging wave travels out along the line; this is again reflected upon reaching the end, and so on. As the wave oscillates backwards and forwards it is diminished by ohmic resistance and insulator leakage; under certain conditions corona losses also occur. As a result of this damping, after some time the whole phenomenon disappears, the line being finally at zero potential.

If the discharging wave encounters, at the end of the line, an apparatus with higher wave resistance than the line itself, e. g. a choke coil, phenomena similar to the foregoing are produced. The pressure wave has an amplitude E, but the current wave must be smaller than in the line, owing to the higher wave resistance. On this account, the values of the currents proceeding from the end of the line fall to that of the second current wave. The same reasons which give rise to a pressure —E by reflection at the open end of a line, here cause a negative pressure wave—the value of which is, however, less than E—to travel back over the line. Upon this wave reaching the point A, the same phenomena occur as described in the previous paragraph. Owing to the reflection of the wave at the end of the line being only partial, and to ohmic resistance and leakage, the oscillation which is set up eventually becomes damped out.

The variation of pressure at the actual point of reflection is interesting—e. g., at the terminal of a transformer. When a discharging wave reaches this point, the potential to earth falls from $+E$ through zero to a value $-E_1$, the absolute value of which is less than E on account of the partial reflection. This pressure continues at the point of reflection while the reflected wave passes to A and the discharge wave following upon it returns the same way in the opposite direction. Upon this reaching the reflection point, the pressure swings over from $-E_1$ to $+E_2$, where E_2 is less than E_1 in the same way that E_1 is less than E (Fig. 2).

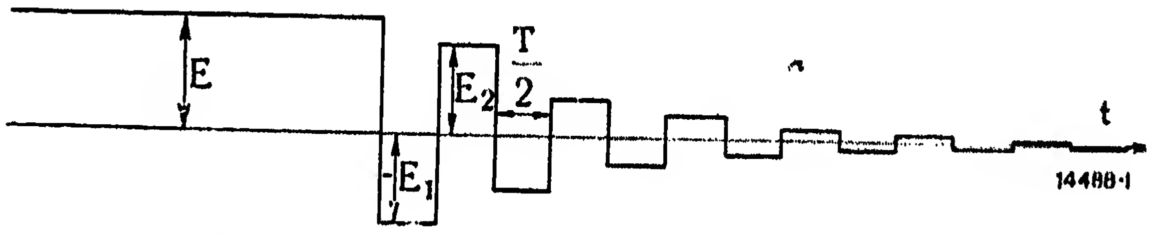


Fig. 2. — Manner in which the potential to earth theoretically varies at a transformer terminal, upon the grounding of the phase concerned.

If $\frac{T}{2}$ = the time interval between two pressure oscillations at the point of reflection,

v = the speed with which the waves travel along the line (the velocity of light), and

l = the distance covered in one direction, the following formula can be written down directly from the foregoing:—

$$\frac{T}{2} = \frac{2\,l}{v} \text{ seconds.}$$

The frequency of the pressure oscillations at the point of reflection is then:—

$$f = \frac{1}{T} = \frac{v}{4\,l} = \frac{75'000}{l} \text{ cycles per second}$$

where T is in seconds and l in km.

For example, if a ground occurs distant 300 m from a transformer terminal, the frequency of the pressure oscillations at the terminal will be:—

$$f = \frac{75'000}{0.3} = 250'000 \text{ per second.}$$

In contrast to the conditions prevailing with travelling waves originating in other ways, the front of those occasioned by short circuits is usually steep; they have all the characteristics of an actual surge. In spite of this, Fig. 2 is only a theoretical representation of what takes place, as it is drawn under the assumption that the wave front is vertical. The damping effect of the conductor produces a wave form for the complete phenomenon which approximates to a damped simple-harmonic oscillation, as shown in Fig. 3.

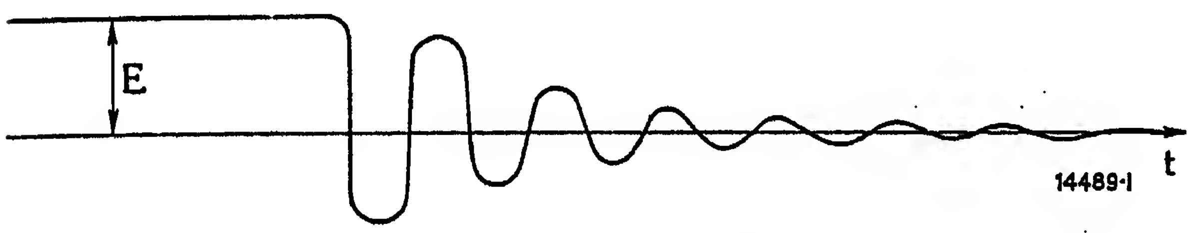


Fig. 3. — Manner in which the potential to earth actually varies at a transformer terminal, upon grounding of the phase concerned.
t. Time.

(b) **Charging Waves.** When a thunder cloud approaches a transmission line, that portion of the line which happens to be in the field of the cloud receives a charge, in accordance with electrostatic laws. Should a stroke of lightning to earth occur in the neighbourhood of the conductor, the field of the cloud becomes zero, and the whole charge on the conductor is suddenly liberated, and begins to move outwards on both sides; i. e., in each direction along the conductor, a current wave begins to travel, the length of which is equal to the length of the original charge. By the laws of induction, the current wave must give rise to a pressure wave, the relation between the amplitudes of the two again being the wave resistance of the line. These charging waves are reflected at the ends of the line in the same way as the discharging waves. As the charges are partly or completely arrested, a concentration takes place at these points, which causes the current wave to move in the opposite direction: a corresponding increase takes place in the pressure wave which is also reflected. Thus, an oscillation of the charging wave over the whole line results, which is eventually damped out as before.

The danger of these phenomena lies in the fact that the sudden increase of pressure in the line under the cloud may occasion a flashover to earth at one of the insulators. This has the result that the relatively harmless *charging* wave with its gradually sloping front is followed by a steep-fronted, high-tension *discharging* wave (see Fig. 4); such surges give rise to the highest electrical stresses to which the insulation of windings is subjected.

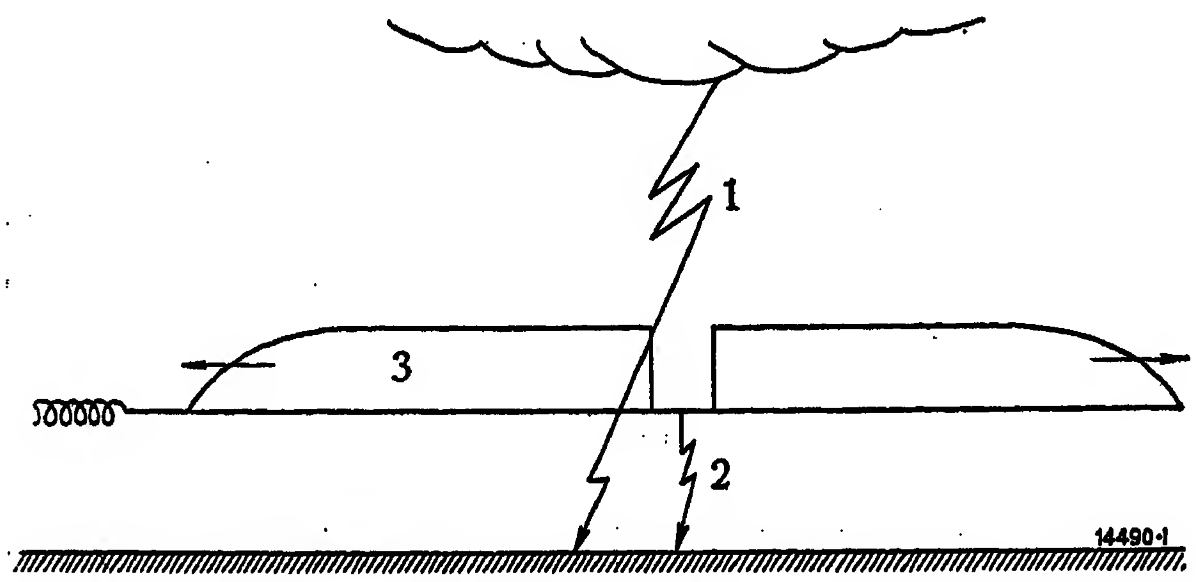


Fig. 4. — Surges caused by a stroke of lightning.
1. Lightning.
2. Ground (flashover of an insulator).
3. Pressure surge.

The hight of the front of surges (discharging waves) is equal to the pressure prevailing at the point of grounding at the instant when grounding takes place. With grounds arising through such causes as defective insulation (cracking of insulators due to temperature or stone throwing, contact with external wires, birds, etc.), it can reach the maximum value of the phase tension. If the load is greatly unbalanced, however, (e. g. if there is already a ground on the system), its highest value will be the maximum working pressure of the system. On the other hand, should the ground occur following an indirect stroke of lightning, it takes the form of a flashover at one of the insulators; thus the amplitude of the surge is in the neighbourhood of the flashover pressure of the insulators employed. This value varies between three or more times the normal pressure in the case of installations working at about 5 kV, and twice the normal for those operating at a higher tension.

II. ELECTRICAL STRESSES OCCASIONED IN THE WINDINGS OF TRANSFORMERS BY SURGES.

In order to obtain an idea of the manner in which the windings of transformers are affected by surges, it is useful to represent the composition of winding diagrammatically. For this purpose, two corresponding points on two successive turns of a cylindrical winding are considered. Each has a definite capacity to the other, and also to earth, and between them lies a turn of the winding having self-induction. These conditions hold good throughout the winding, so that the whole may be closely represented by a diagram as shown in Fig. 5. If such a system be

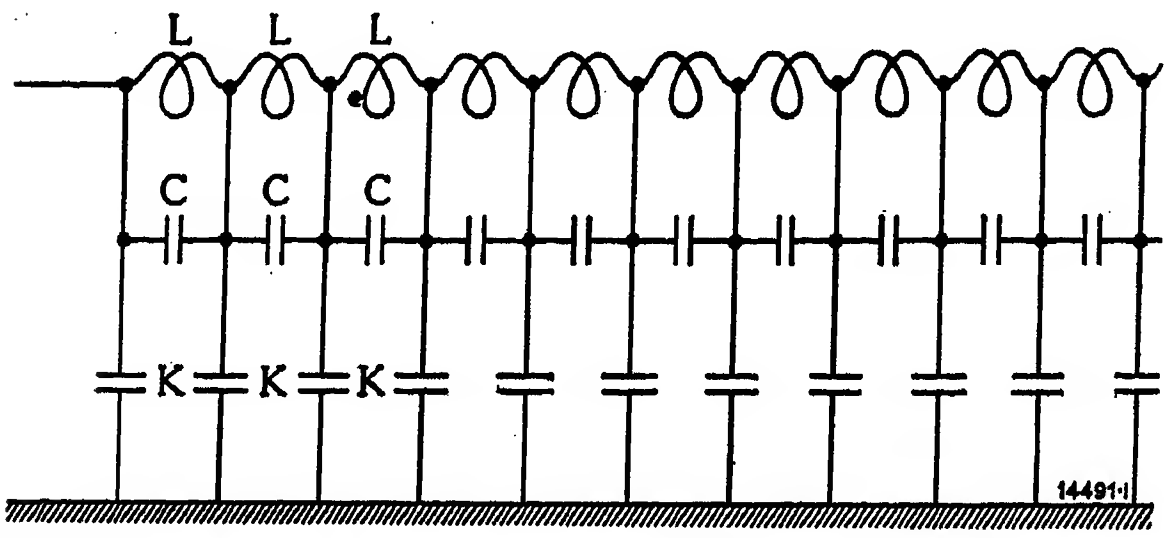


Fig. 5. — Diagrammatic representation of the effective composition of a transformer.
L. Inductances of the turns.
C. Mutual capacities of the turns.
K. Capacities of the turns to earth.

suddenly subjected to quickly changing conditions, they spread at first owing to the help of the capacities, as the inductances oppose any rapid changes. Owing to the connection of the capacities in series and parallel, as indicated, the distribution of the pressure at the first instant must be similar to that over a chain of suspension insulators: the pressure drop over the first capacity C in Fig. 5 is greatest, those over the remainder decreasing in about equal proportions. At the same time, these capacities begin to discharge into the inductances connected in parallel with them; the internal oscillations which occur here, and the effects of the mutual induction between the windings, are not readily determined. It is, however, sufficient for the general comprehension of the test results, which will be given, to note the following three points: —

1. Transformers consist of a number of oscillatory circuits (inductance and capacity connected in series).

2. Quickly changing phenomena, such as surges, at first spread in the turns of a winding owing to the system of mutual capacity and capacity to earth. The result is a distribution of pressure between the neighbouring coils similar to that with a suspension insulator, so that the pressure drop is greatest at the commencement of the winding and thence continuously diminishes.

3. The capacities discharge over the inductances of the corresponding portion of the winding. Should these phenomena (the effects of pressure at the end of a conductor due to reflection of pressure waves) occur with a definite frequency which coincides with the natural frequency of the internal oscillatory circuits, it is to be expected that resonance effects, which will give rise to large differences of pressure between neighbouring portions of the winding, will be set up in the transformer.

This reasoning is confirmed by experience. More than half the coil failures attributable to stresses set up by surges take place at the beginning of the winding. Such failures are also known to occur, however, at other points in the winding, and the assumption of their being due to weak spots in the insulation is very rarely justifiable, internal oscillations being the usual cause of the dangerous pressures between the layers or coils affected. The results represented in Fig. 6, which were obtained during grounding tests, support this theory. Artificial grounds were

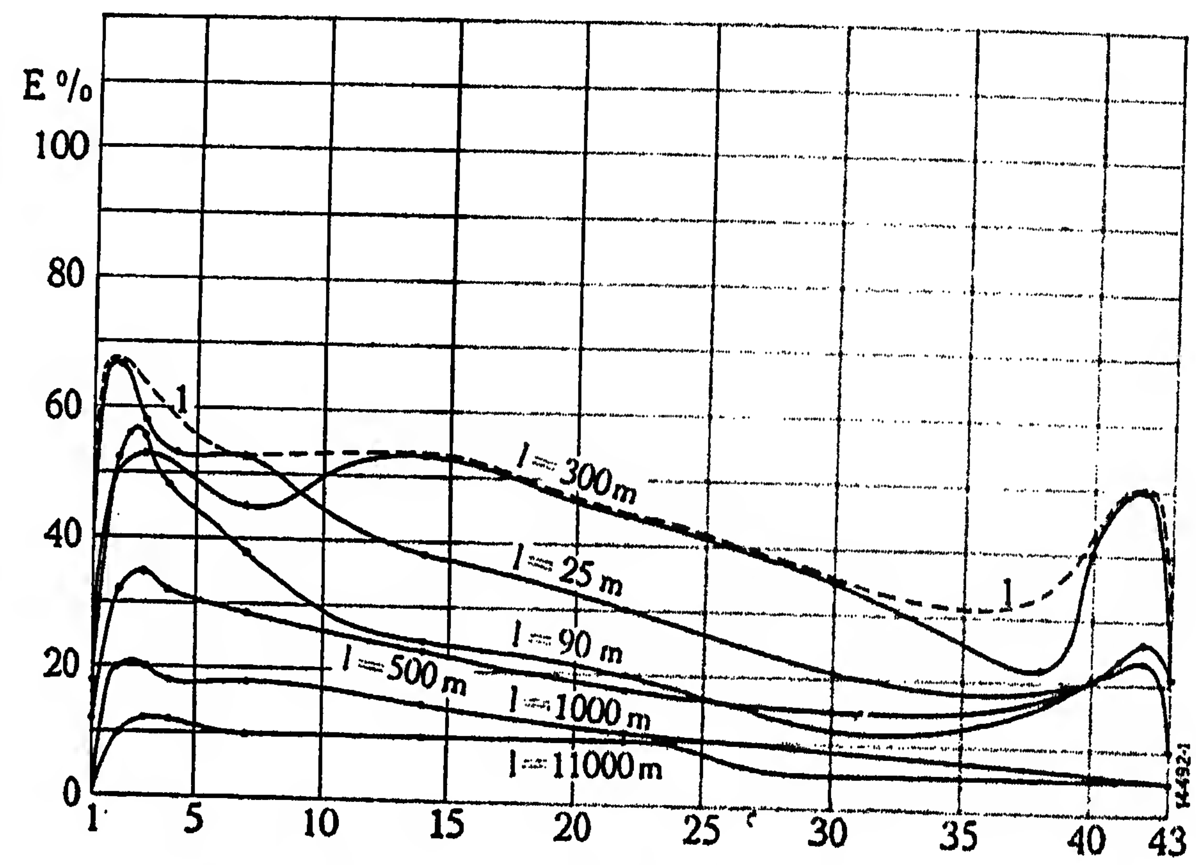


Fig. 6a. — Distribution of the surge pressure over the coils of a transformer winding upon a ground occurring at a distance l from it.
E. Amplitude of the surge.
1. Envelope curve.

caused, at various distances from the transformer, on an overhead transmission line. At the grounding points a spark gap was connected consisting of spheres set at a definite distance apart. The pressure of the system was raised till a flashover occurred, followed by a ground. The amplitude of the surge was then equal to the pressure for sparking over the gap between the spheres, the surge pressures between tappings over individual coils of the transformer (two layers) were measured by a spark gap ionised by a mercury vapour lamp. The ordinates of the curves in Figs. 6a and b are the surge pressures measured in this way and given as percentages of the amplitude of the main surge; the horizontal axis in Fig. 6a is divided and numbered according to the transformer coils concerned.

The curves show clearly that, with the point of grounding furthest from the transformer, the stressing of the coils due to surges decreases from the beginning of the winding towards the middle, and under certain circumstances increases again slightly at the very end. The importance which may be attained by internal resonance effects is shown by the curve for the distance l = 300 m. It will be seen from this that the pressure drop over individual coils at the middle or end of the

winding is as great, or nearly as great as can occur at the beginning.

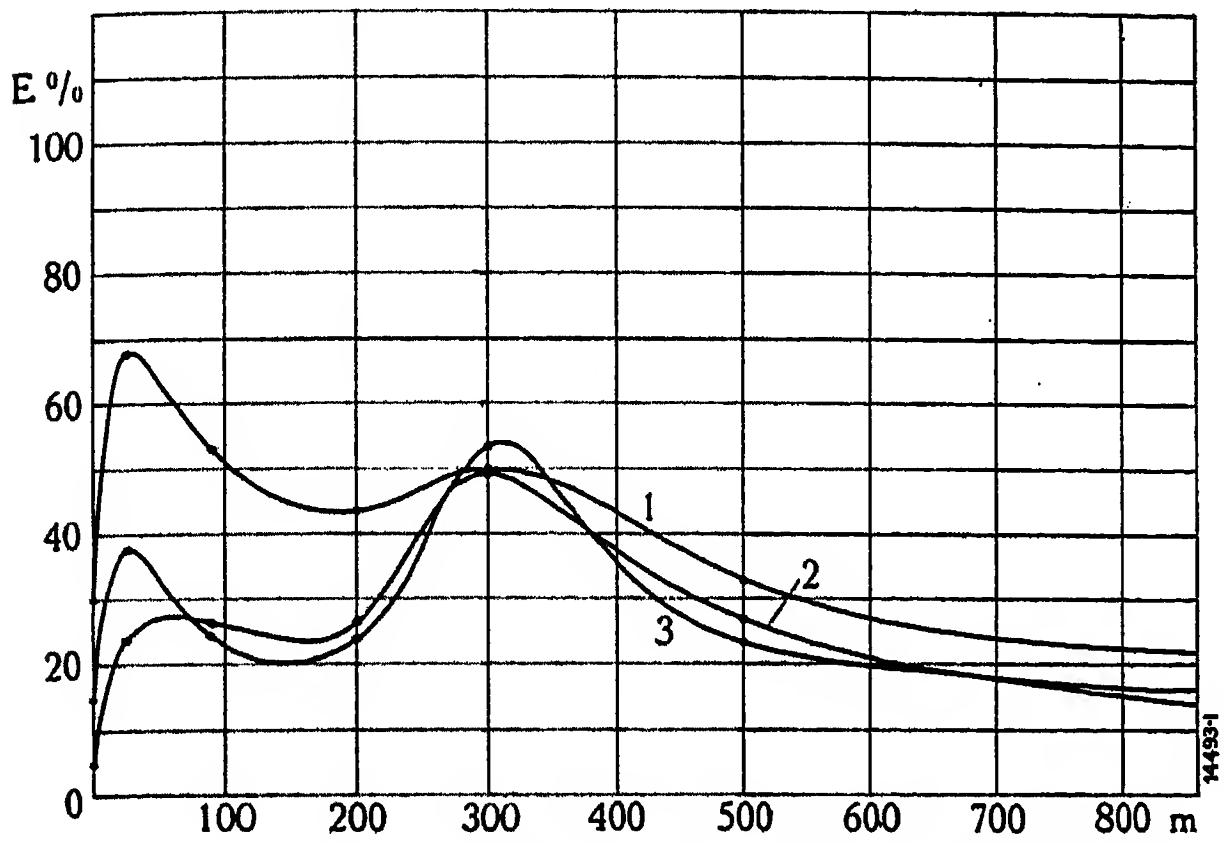


Fig. 6b. — Variation of the surge pressure over single coils of a transformer winding with the distance of the grounding point from the transformer.
E. Amplitude of the surge.

Fig. 6b shows, as a function of the distance of the grounding point, the extent to which coils at the beginning, middle, and end of a transformer winding are stressed. It clearly indicates that these phenomena are the result of resonance. One can also form an idea of the extent of stresses set up by these surges from the following facts: —

The transformer on which the tests were made is rated for a pressure of 57 kV. The flashover pressure of the insulators in such a system is about 130 kV, so that the surge resulting from an insulator flashover, following an indirect stroke of lightning for instance, would have an amplitude of 130 kV. The normal pressure drop over a coil is about 800 V. The surge stress between two coils can be as much as 67 % of the amplitude of the main surge, i. e., here 88 kV, which is a hundred times the normal working pressure.

The danger of these surges is certainly not accounted for entirely by the magnitude of the pressure, but to a great extent also, by the time during which it exists in the coil considered, which may be in the order of $1/10^5$ seconds.

Finally, it may be mentioned that the above results are not numerically applicable to other transformers, as all data such as mutual capacity of the coils and layers, and their capacity to earth, depend essentially upon individual details of construction.

III. METHODS OF PROTECTION AND THEIR ACTION.

At the present time, four methods of protection against the effects of surges are in use:

1. The strengthening of the insulation of the first coils of each winding.

2. The connection of choke coils between the transformer and the line.

3. The connection of condensers between the transformer and earth.

4. The strengthening of the insulation of the whole winding.

The object of strengthening the insulation of the first coil is to guard against the heavier stresses which occur at this portion of the winding.

The reason for the employment of choke coils is that, owing to their resemblance to the transformer windings themselves, they sustain the heavy stresses to which the first coils of the latter would otherwise be subjected.

The use of condensers is supported by the reasoning that, if they are connected to the terminals of a transformer and a surge (discharging wave) occurs on one phase, no effect is felt at the terminals until the condenser begins to discharge. During the discharge the pressure only falls gradually—in the usual form of circuit, the fall of pressure is slower the larger the capacity—and thus, the pressure variation at the transformer terminals is rendered slower. In other words, the condensers have the effect of rendering the wave front less steep and diminishing the stress between the coils.

In the course of the tests referred to, it was sought to determine the relative value of these means of protection. To this end, the stresses were measured for each coil throughout one group of windings with different

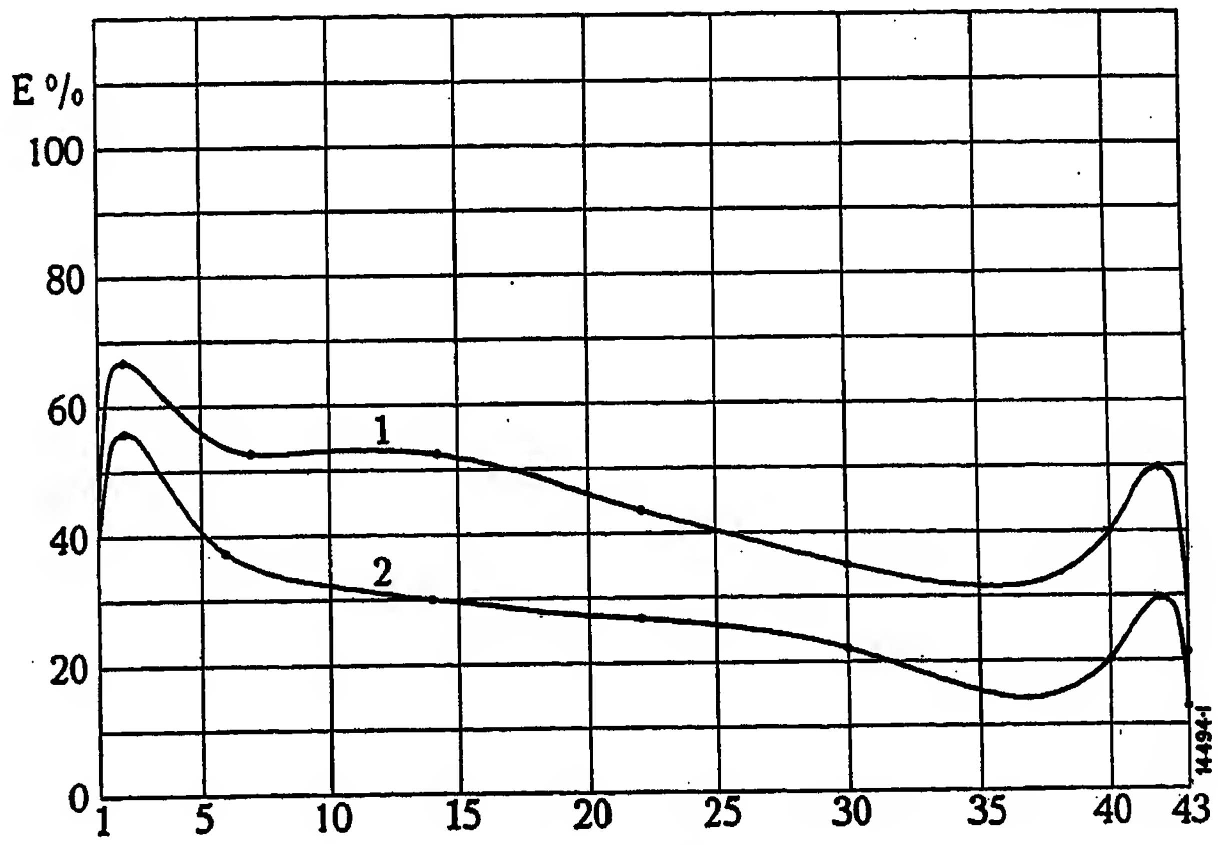


Fig. 7. — Distribution of the surge pressure over the coils of a transformer winding; envelope curves of measurements made with various distances between the grounding point and the transformer.

Curve 1. Insulation of the first and last coils strengthened.
Curve 2. All coils equally insulated.
E. Amplitude of the surge.

values of l, the distance between the transformer and the point of grounding. These tests were identical with those illustrated in Fig. 6a except that in this case the various protective measures were employed. The results are shown in Figs. 7 and 8. The curves given are the envelopes, i. e., they are drawn to pass through all the maximum values obtained for the particular set of conditions to which they refer, in the same way as curve 1 in Fig. 6a. Thus, they include the highest surge stresses which can occur under any circumstances between the individual coils of the transformer tested.

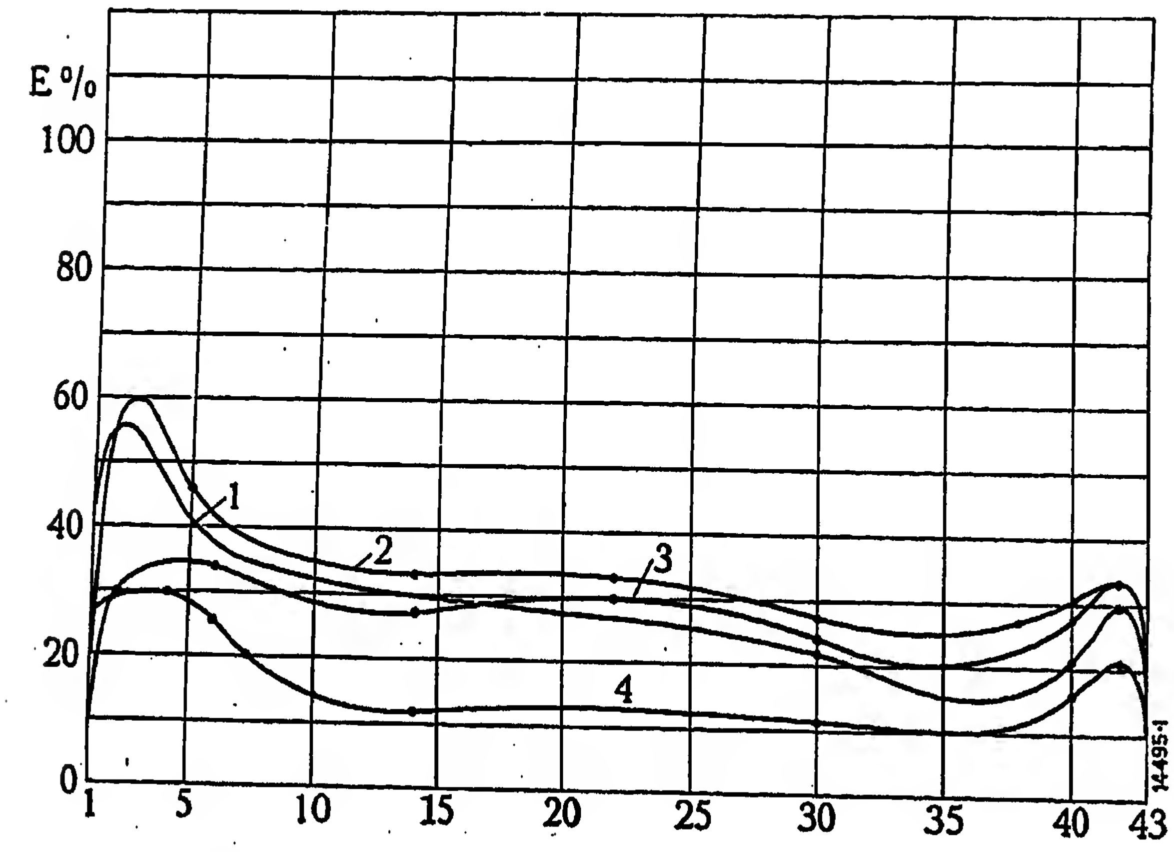


Fig. 8. — Distribution of the surge pressure over the coils of a transformer winding; envelope curves of measurements made with various distances between the grounding points and the transformer. Coils equally insulated throughout.

Curve 1. Transformer without any special protection.
Curve 2. Choke coil of 0·5 mH connected between line and terminal on each phase.
Curve 3. Choke coil of 3·0 mH connected between line and terminal on each phase.
Curve 4. Capacity of 0·01 μF connected between terminal and earth on each phase.
E. Amplitude of the surge.

As can be seen in Fig. 7, the strengthening of the insulation of the beginning of the winding results in an increase of surge stress throughout the transformer. This is readily explained by the fact that the increased insulation involves a reduction in the number of turns of the coils concerned, and, therefore, of their inductance. This reduction amounts to about 20 % in the first coils and 66 % in the last; the dielectric strength at both these points being about 75 % higher than the normally insulated coils. In this way, a marked increase in safety is secured, particularly in the case of the first coils. Unfortunately, this advantage is entirely nullified by the fact that in the centre coils, the insulation of which is not strengthened, an increase of about 75 % occurs in the surge stress. The partial strengthening of the insulation can, therefore, not be considered advantageous.

As regards the use of choke coils as a means of guarding against the effects of surges, curves 1, 2 and 3 in Fig. 8 show that the many doubts expressed with regard to their efficiency as a means of protection are well founded. Small inductances — e.g., 0·5 m H, a size of protective choke coil which is frequently to be found in installations — even increase the danger to which transformers are subjected by surges, but choke coils of the order of 3·0 m H afford a certain amount of protection to the first coils, but for the centre and end of a winding, where the effect of internal resonance is most dangerous (see § II), they have no protective value whatever. Therefore, a certain hesitation regarding the use of choke coils in this connection can be understood.

The case of condensers is different however, these being a definitely valuable means of protection under all circumstances. As can be seen by comparing the curves 1 and 4 in Fig. 8, when a capacity of the order of 0·01 μ F was used, the surge stresses throughout the transformer were at least half those occurring when no special means of protection was employed.

From the point of view of their construction, some types of condenser, to-day on the market, make a very good impression. The use of such apparatus for the diminution of surge stresses in transformers is, therefore, feasible. On the other hand, it must be pointed out that they require a great deal of space, and their cost is high. Thus it happens that the use of efficient protective apparatus opposes the present welcome tendency to simplicity.

For these reasons, Brown, Boveri & Co. have sought a solution to the problem in strengthening the insulation of the windings of large transformers throughout, although not by increasing the distance between the turns, but by the choice of an insulating material of higher dielectric strength.

The foregoing may be summarised as follows:—

1. Strengthening of the insulation of the first coils has only relative protective value.
2. Choke coils, as a means of protection are to be avoided.
3. Condensers may be employed for this purpose, but are costly and occupy much space.
4. Improvement of the insulation of the complete winding is the only satisfactory solution from all points of view.

IV. SURGE TESTS OF TRANSFORMERS.

In the previous section it was shown that transformers may be protected against the effects of surges by the use of condensers but that the construction of "surge-proof" transformers is a much better solution. If, however, certain properties are attributed to, or required of a machine or piece of apparatus, the possibility of its passing a corresponding test is implied. Thus, the usual tests to which transformers are subjected in the course of manufacture, such as the determination of the transformation ratio, measurement of the losses, pressure tests, etc., must be supplemented by surge tests such, for example, as laid down in the new instructions for testing issued by the Schweizerischer Elektrotechnischer Verein. In such a test, the transformer in question must be required to stand a definite surge effect for a certain time, its extent to be fixed by agreement. Further, the occurrence of a short circuit in the windings must be readily ascertained and the position of the defect clearly defined. The manner in which these conditions were satisfied by the method of testing developed by Brown, Boveri & Co. is not dealt with in the present article but is reserved for separate treatment on a future occasion.

Together with the other tests, surge tests have two purposes to fulfill. Primarily they assist the manufacturing firm in determining the true value of their existing types, so that unsatisfactory methods of construction may be either improved or eliminated entirely. Also, in the case of individual pieces of apparatus, when the insulation of the windings is damaged or weakened during the process of manufacture, the fact is discovered before they are put into actual service.

It is to be expected that, in this way, it will be possible to reduce considerably the number of flashovers between layers and coils in transformers which are in good condition and well looked after, in the same way that it is possible to reduce flashovers to earth to an exception by laying down sufficiently severe conditions for the pressure tests.

V. APPENDIX.

In the foregoing article it was mentioned that an exact investigation of the phenomena dealt with could only be carried out with the help of higher mathematics.[1] It is quite possible, however, to understand the general laws concerned, with a more elementary mathematical knowledge. In the hope that it may prove of interest to certain readers, such a treatment of the problem is given in this appendix, although no originality is claimed for the method adopted.

[1] Steinmetz, Proceedings of AIEE, 1918.

The following symbols are employed:—

- E = Amplitude of the pressure wave = Potential of the line to earth before discharge.
- I = Amplitude of the current wave.
- t = Time interval.
- t_1 = Moment considered.
- v = Speed with which the wave travels along the line.
- x = Length of the line.
- x_1 = Distance of the point considered from the grounding point.
- $\varkappa$ = Capacity to earth of unit length of the line.
- λ = Self-induction of unit length of the line.
- ρ = Ohmic resistance of unit length of the line.
- ρ_i = Insulation resistance of unit length of the line.
- γ = Insulation conductance of unit length of the line $= \frac{1}{\rho_i}$.
- Δ = A small difference or variation of the quantity to which it is applied, e.g., ΔE represents a small variation of pressure, either at a certain fixed point in the line during the time interval Δt, or over a short length of line Δx at a definite instant. As the wave progresses along the line, these two methods of expression are in effect identical so long as the character of the phenomenon does not change with the passage of the wave. This condition is practically realised as long as the character of the conductor undergoes no essential change, e.g., a continuous cable or overhead line. Similarly, ΔI represents a small variation in current.

The resistance of the line and conductance of the insulators are at first neglected, so that the relation between current and pressure is determined only by the laws of inductance and capacity. These will first be briefly considered.

1. Law of capacity. If two conductors are connected to a source of current, a potential difference E_c being applied, an electrostatic field is established in their neighbourhood. This is a state of tension in space, such that a difference of potential exists between any two points. The distribution of this field varies according to a definite law and, in air at least, it may be considered proportional to the value of E_c. As with all states of tension, the

existence of an electrostatic field implies an accumulation of energy which is distributed throughout the space concerned, and the amount of which is given by the expression:

$$A_e = C \cdot \frac{E_c^2}{2},$$

where C represents the mutual capacity of the conductors. Should the value of E_c vary, a readjustment of the energy takes place in the form of a current I_c. This follows the law of capacity:—

If a circuit contains a capacity C and the pressure across it E_c varies by the amount ΔE_c during the interval of time Δt, a current I_c flows in the circuit which is given at any instant by the equation:

$$I_c = - C \cdot \frac{\Delta E_c}{\Delta t},$$

a linear variation of ΔE_c during the time interval Δt being assumed. In most instances Δt is chosen so small that $\frac{\Delta E_c}{\Delta t}$ may be replaced by the differential $\frac{d E_c}{dt}$.

2. **Law of induction.** A conductor through which a current I flows is surrounded by a magnetic field. This is indicated by the fact that a magnetic needle experiences a definite force at all points in the space around the conductor, and, when the latter is straight, it tends to set itself, under the action of this force, perpendicular to the radius vector and in a plane perpendicular to the conductor. The energy A_m distributed throughout the space surrounding a conductor is given by:

$$A_m = L \cdot \frac{I^2}{2},$$

where L is the self induction of the circuit. If the value of I changes, the restoration of this distribution of energy to a state of equilibrium requires or gives rise to an electromotive force. This is in accordance with the law of induction:—

If the current in circuit varies by ΔI during the interval ot time Δt, the instantaneous value of the E.M.F. involved is given by the equation:

$$E = - L \cdot \frac{\Delta I}{\Delta t}.$$

During the interval Δt, the variation of I with time must be linear, and in an accurate investigation, the differential $\frac{dI}{dt}$ must be substituted for $\frac{\Delta I}{\Delta t}$.

Some idea of the connection between the electrostatic and magnetic fields, may be obtained by consideration of the analogy of a quantity of water. This water, being subjected to the force of gravity represents a certain amount potential energy. If it is partly allowed to move in the direction of the force of gravity, eddies are set up in planes perpendicular to this force. The eddying of the liquid is thus a form of kinetic energy, which is obtained by the conversion of some of the potential energy of the stationary liquid. An electrostatic field may be compared with the action of the force of gravity, and a magnetic field with the eddying and, in this sense, it may be said that the electrostatic field is a state of potential energy while the magnetic field is a state of kinetic energy.

When studying the effect of travelling waves in transmission lines it is necessary to keep in mind the following:—

If a conductor is raised to a given tension with regard to earth, a certain amount of potential energy is stored in the electrostatic field between them. If the whole system were divided into sections, conductor eloctrostatic field, and energy would be so divided that the amount of energy would be proportional to the length of the section in each case, providing the nature of the line remained constant. Thus, the capacity of each section may be considered proportional to its length and it is possible to refer to the capacity per unit length.

The same reasoning holds good for the magnetic field, and a corresponding definition of inductance per unit length of the line may be given.

We now pass on to the consideration of travelling waves themselves. The phenomena from which these take their origin have already been described in the

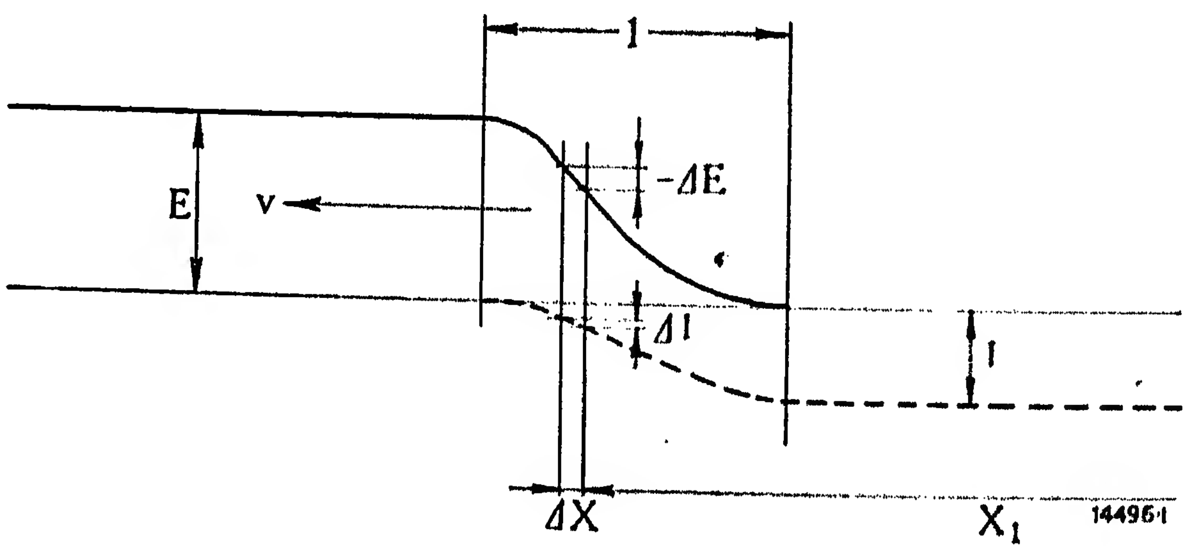


Fig. 9. — Discharging wave traversing a line.
1. Wave front.

first section of this article. The more general expressions applicable to any point on the line are here derived.

If, at a given instant, a *charging wave* reaches the neighbourhood of a point, distant x from the point of grounding (see Fig. 9), and if an element of the line be considered, Δx in length, over which the front of the wave is passing, a pressure drop ΔE occurs across the element. The current which flows as a result of the change $(-\Delta E)$ in pressure applied to the capacity $\varkappa \cdot \Delta x$ is ΔI. The inductance of the conductor at that point is given by $\lambda \cdot \Delta x$. Then, according to the laws of inductance and capacity:

$$-\Delta E = -\lambda \cdot \Delta x \cdot \frac{\Delta I}{\Delta t} \qquad \text{(a)}$$

$$\text{and } \Delta I = -\varkappa \cdot \Delta x \cdot \frac{-\Delta E}{\Delta t} \qquad \text{(b)}$$

From the expression for the speed with which the wave travels:

$$v = \frac{\Delta x}{\Delta t}$$

we have $\Delta t = \frac{\Delta x}{v}$, and by substitution in equations (a) and (b):

$$-\Delta E = -\lambda \cdot v \cdot \Delta I \qquad \text{(a')}$$

$$\text{and } \Delta I = \varkappa \cdot v \cdot \Delta E \qquad \text{(b')}$$

$$\therefore v = \frac{1}{\sqrt{\lambda \cdot \varkappa}} \qquad \text{(c)}$$

$$\text{and } \Delta E = \sqrt{\frac{\lambda}{\varkappa}} \cdot \Delta I \qquad \text{(d)}$$

$$\text{Now } E = \Sigma \Delta E \text{ and } I = \Sigma \Delta I$$

$$\therefore E = \sqrt{\frac{\lambda}{\varkappa}} \cdot I \qquad \text{(d')}$$

Thus, it is evident that the speed of the wave depends upon constants of the system which, in the case of an overhead transmission line, are always such that v is practically equal to the speed of light.

The expression $\sqrt{\frac{\lambda}{\varkappa}}$, as already stated, is known as the wave resistance of the line. It is a constant of the system in the same way as λ and $\varkappa$. For overhead lines its approximate value is given by: $\sqrt{\frac{\lambda}{\varkappa}} \simeq 800\,\Omega$.

The conditions under which *charging phenomena* take place may now be easily represented. If a charging wave approaches a point x on the line, the conditions obtaining may be represented as in Fig. 10.

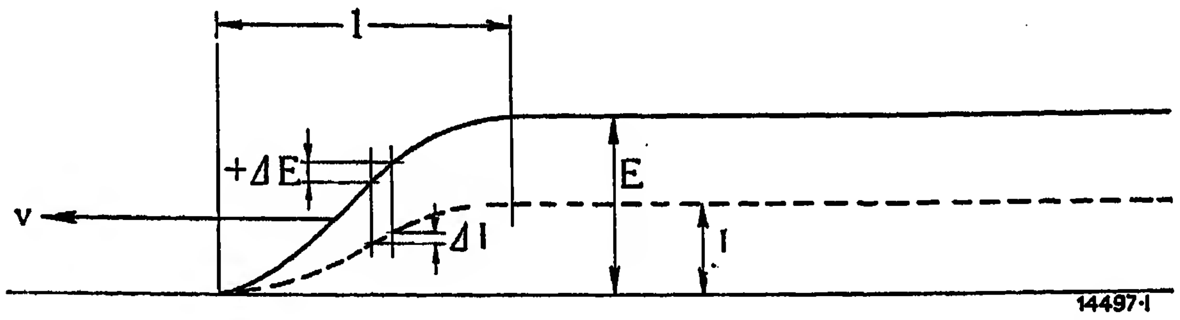


Fig. 10. — Charging wave traversing a line.
1. Wave front.

If the increase of pressure across the element Δx of the line is ΔE, and at any single point x the pressure changes by the amount ΔE in the time interval Δt, a current ΔI flows into the capacity $\varkappa \cdot \Delta x$. The laws of capacity and inductance here again apply so that:

$$\Delta E = -\lambda \cdot \Delta x \cdot \frac{\Delta I}{\Delta t}$$

$$\text{and } \Delta I = -\varkappa \cdot \Delta x \cdot \frac{\Delta E}{\Delta t}.$$

These two expressions may be developed in the same way as for discharging phenomena and with exactly the same results.

It is interesting to follow the changes of energy brought about by these travelling waves.

Before the discharge, the energy stored in the electrostatic field around the length of line Δx was:

$$A_{e_x} = \varkappa \cdot \Delta x \cdot \frac{E^2}{2}$$

As no current flows, there is no energy in the form of a magnetic field. After the wave front has passed, however, there remains at the same point only the magnetic energy:

$$A_{m_x} = \lambda \cdot \Delta x \frac{I^2}{2}.$$

If E be expressed in terms of I (or vice versa) according to equation (d'), which is the expression for wave resistance, it follows that:

$$A_{m_x} = A_{e_x}.$$

That is to say, the energy of the electrostatic field is entirely replaced by that of a magnetic field, and vice versa, when reflection of a discharging wave takes place. Thus, no transmission of energy occurs, but only a transformation.

The case of the charging wave differs in this respect. Upon a charging wave travelling over a section of the line, both electrostatic and magnetic fields are established in the surrounding space, where previously

no field at all existed. The whole energy of the wave is so distributed that, at every point, electrostatic and magnetic fields carry the same amount of energy. On the other hand, in the region where the wave originated, the two fields break down so that a transmission of energy is bound to occur.

The practical result of this is that at no point in the line can any greater storage of energy take place on the occurrence of a discharging wave, than the amount of energy already distributed at that point. On the other hand, with charging waves the storage of additional energy is possible, at reflection points for instance. This constitutes a danger which threatens the insulators but not necessarily the internal insulation of the transformer windings. As already mentioned in the opening sections, the latter are affected chiefly by the steepness of the wave front and the frequency of the reflections.

In conclusion, the effects of line resistance and insulation leakage may be briefly considered. Their damping action is simply explained. The insulation resistance of a length Δx of the line is given by $\frac{\rho_i}{\Delta x} = \frac{1}{\gamma \cdot \Delta x}$ so that if the point x is at a potential E to earth, the energy converted into heat on account of this insulation resistance is:

$$A_{e_v} = \frac{E^2}{\rho_i} \cdot \Delta x = \gamma \Delta x \cdot E^2$$

If the current I flows in the conductor at the same point, the ohmic resistance $\rho \cdot \Delta x$ involves a certain amount of energy:

$$A_{m\,v} = \rho \cdot \Delta x \cdot I^2$$

This conversion into heat is naturally irreversible, and thus a dissipation of the wave energy takes place until it entirely disappears.

Finally, it would be well to note that the above investigation is carried out on the basis of an open line consisting of a single conductor, and that the discharging phenomena are considered only for direct current. With a line working on two or more phases, however, further electrostatic fields are set up between the individual conductors, which correspond to the pr essure of the system, and also further magnetic fields porportional to the load current. It is found, on a more accurate investigation, that the principle of superposition may here be employed, so that, when one phase is grounded, the wave phenomena are superposed upon those arising from ordinary working conditions. Thus, the energy of the electrostatic field between the phase concerned and earth is liberated when grounding occurs and is dissipated by the damping effect as described.

G. Courvoisier. (G.T.S.)

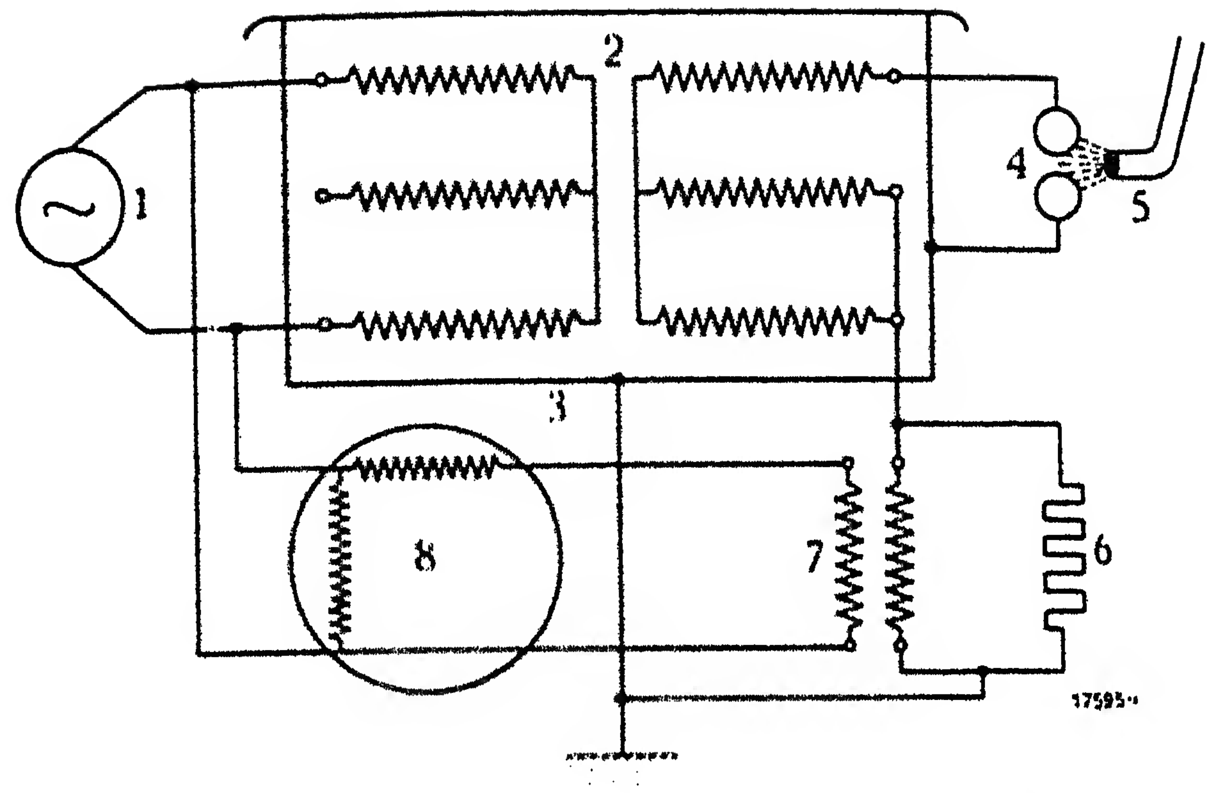


Fig. 5. — Diagram of connections for surge test.

1. Supply at frequency equal to or higher than that of the apparatus tested. The sources of supply can be protected from the influence of surges in various ways, e. g., condensers or choke coils.
2. Transformer to be tested.
3. Transformer tank.
4. Spark gap with compressed-air blast.
5. Compressed-air pipe.
6. Resistance.
7. Testing Transformer.
8. Induction regulator.

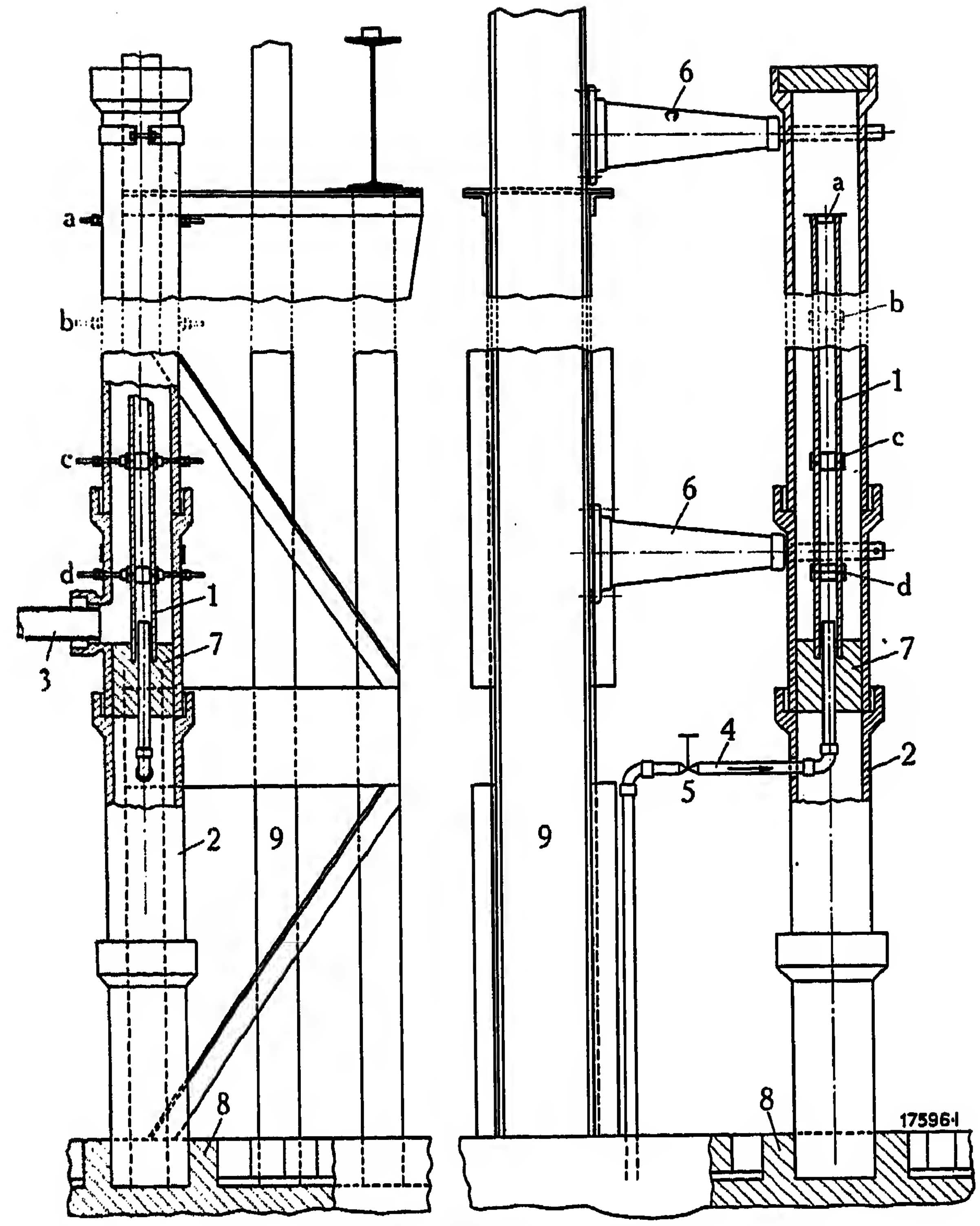


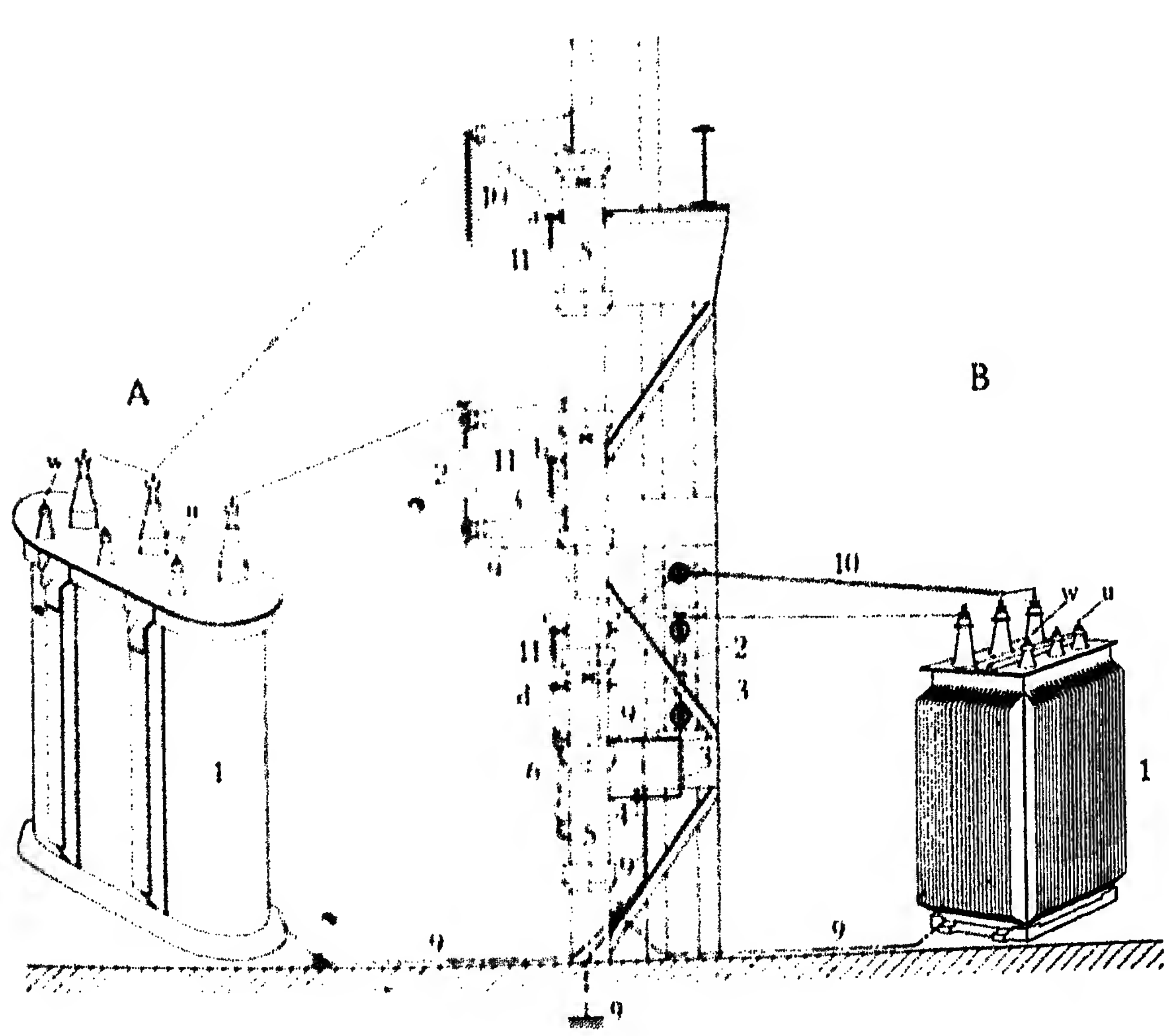
Fig. 6. — Water resistance for surge tests.

1. Earthenware pipe for ascending water.
2. Earthenware pipe for descending water.
3. Water outlet.
4. Water inlet.
5 Water stop-cock.
6. Supporting insulators.
7. Stop.
8. Foundation.
9. Steel column.

a, b, c, d. Tappings.

voltage at the terminals not under test does not become inadmissibly high. If the two untested terminals of a three-phase transformer are connected, a single resistance may be used. This connection does not influence the surge stress set up.

The most favourable values for the ohmic resistance and the velocity of the blast may easily be determined by the appearance of the spark. With the correct choice of these conditions the spark will be violet or blue, while the formation of an arc of yellow colour indicates too low a resistance value or too weak an air blast. Fig. 4 a shows the arc set up when the blast is not in use, and Fig. 4b that when the correct blast is applied. The difference between the two pictures is easily seen.



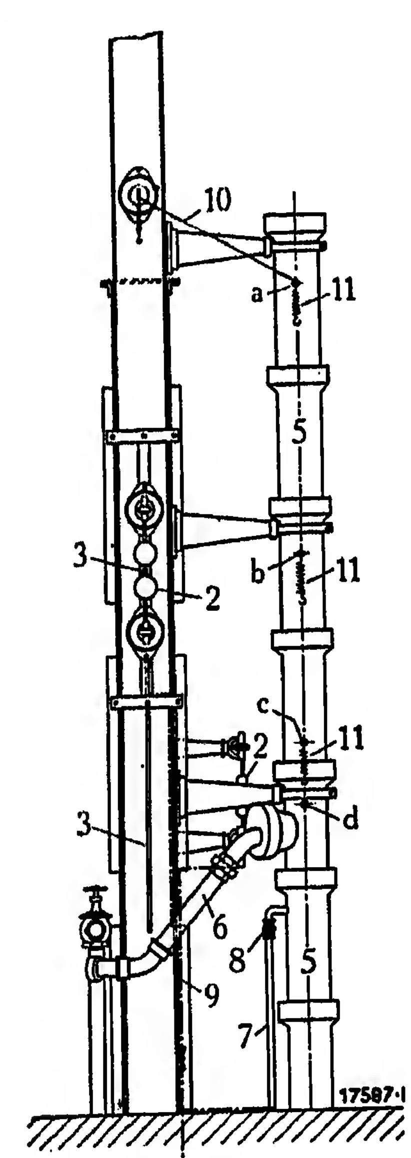


Fig. 7. — Bays for surge tests.

A. Bay for testing large transformers.
B. Bay for testing small transformers.

1. Transformer under test.
2. Spark gap.
3. Compressed-air supply.
4. Compressed-air cock.
5. Water resistance.
6. Water outlet.
7. Water inlet.
8. Water supply cock.
9. Earth.
10. Connection between transformer and water resistance.
11. Spiral spring to short-circuit the different resistance terminals.

a, b, c, and d. Resistance tappings for pressures smaller than 135,000, 60,000, 24,000, and 8000 V.

The object of this method of testing is not only to submit the winding to a surge but also to indicate any defect which could not be discovered by the ordinary examination. To obtain the latter result a pressure approximately equal to the normal value is applied to the terminals of the apparatus tested. Any defective places would be burnt through and the defect immediately localised.

Transformers can be tested at their normal frequency, by this method, and be subjected to surges the amplitude of which approaches the applied maximum pressure, i. e., $1 \cdot 3\ E_v$ in normal circumstances, E_v being the working pressure. An increase of the amplitude of the surge is obtained by increasing the frequency of the source of supply. If the frequency can be doubled without the induction becoming excessive it is possible to increase the amplitude up to $2 \cdot 6\ E_v$.

When it is desired to raise the amplitude of the surge above this value (e. g. for experimental purposes), suitable apparatus may be connected to the transformer as shown in Fig. 5. The transformer for the production of the auxiliary pressure is supplied from the same source, and therefore with current at the same frequency as the transformer to be tested.

The phase of this auxiliary voltage must be such that it is added to the excitation voltage of the coil tested; hence at the terminal of the latter a higher potential to earth is produced. With this arrangement it is possible to stress the transformer with a surge having an amplitude equal to that of its test pressure. The increase of the amplitude of the surge is possible by this method, a great advantage since the method is the same for ordinary and laboratory testing.

The design of the water resistance used in the transformer testing department of Brown, Boveri & Co., Baden is shown in Fig. 6. The resistance is formed by spring water kept in circulation to avoid undue heating. The water rises in the inner tube and flows down the outer tube, which also serves as a protective covering. Since the water in the outer tube is not under pressure, no special precautions need be taken respecting the outlet.

Fig. 7 shows the arrangement of the surge-testing bays. On the right is shown that for testing small transformers, and the spark gap for small surge tests, while on the left the bay for testing large transformers can be seen. Each spark gap is provided with a tube supplying compressed air, the flow of which can be controlled by a cock.

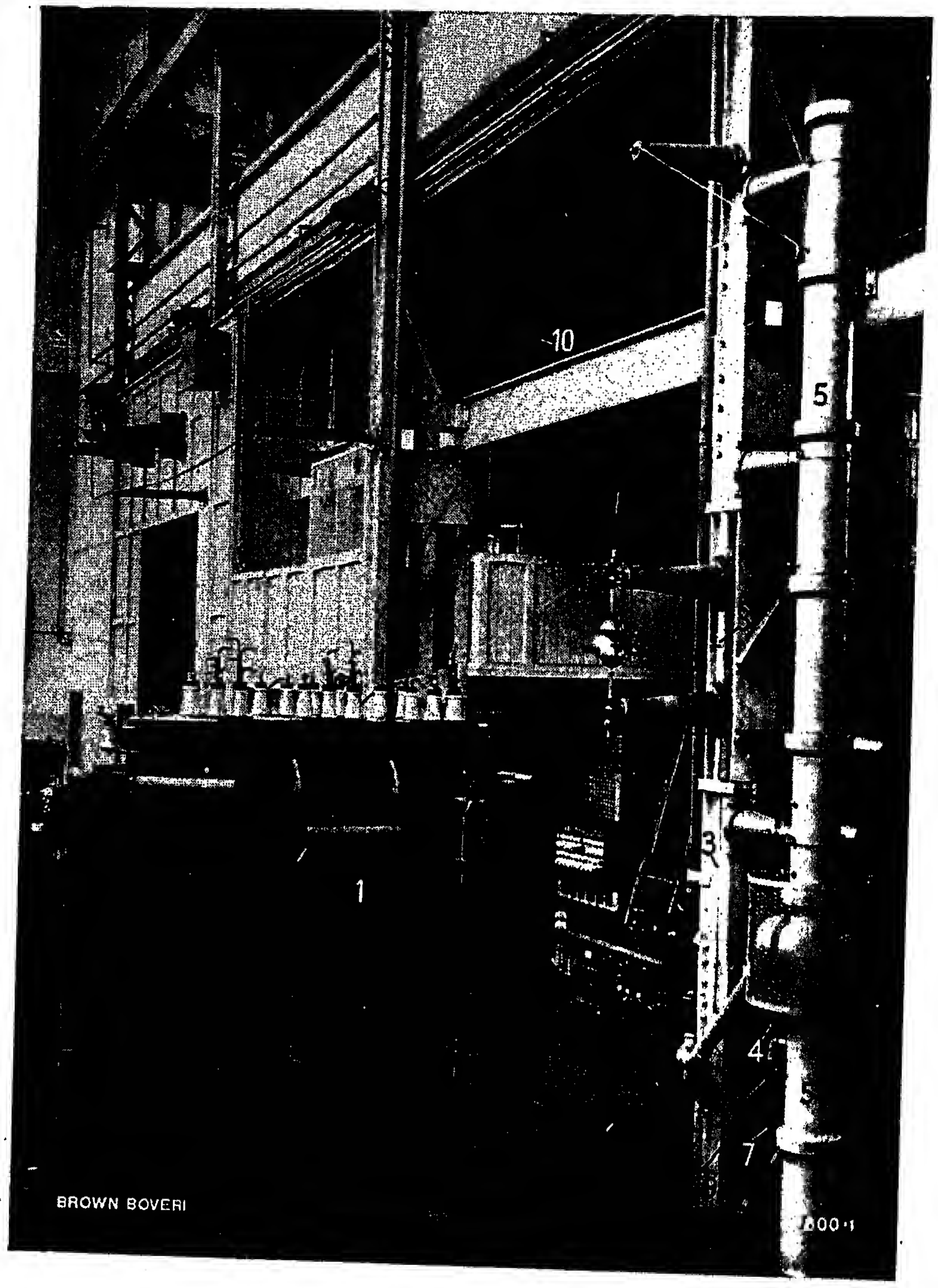


Fig. 8. — Surge test on transformer for 660 kVA and 12 kV.

1. Transformer under test.
2. Spark gap.
3. Compressed-air pipe.
4. Compressed-air cock.
5. Water resistance.
6. Water outlet.
7. Water inlet.
8. Water supply cock.
9. Earth.
10. Connection between transformer and water resistance.
11. Spiral spring to short-circuit the different resistance terminals.

Fig. 8 shows the testing of a transformer for 660 kVA and a pressure of 12 kV. The method of testing described above has proved very suitable for research purposes, and also any manufacturing defect would be discovered before the apparatus left the workshops.

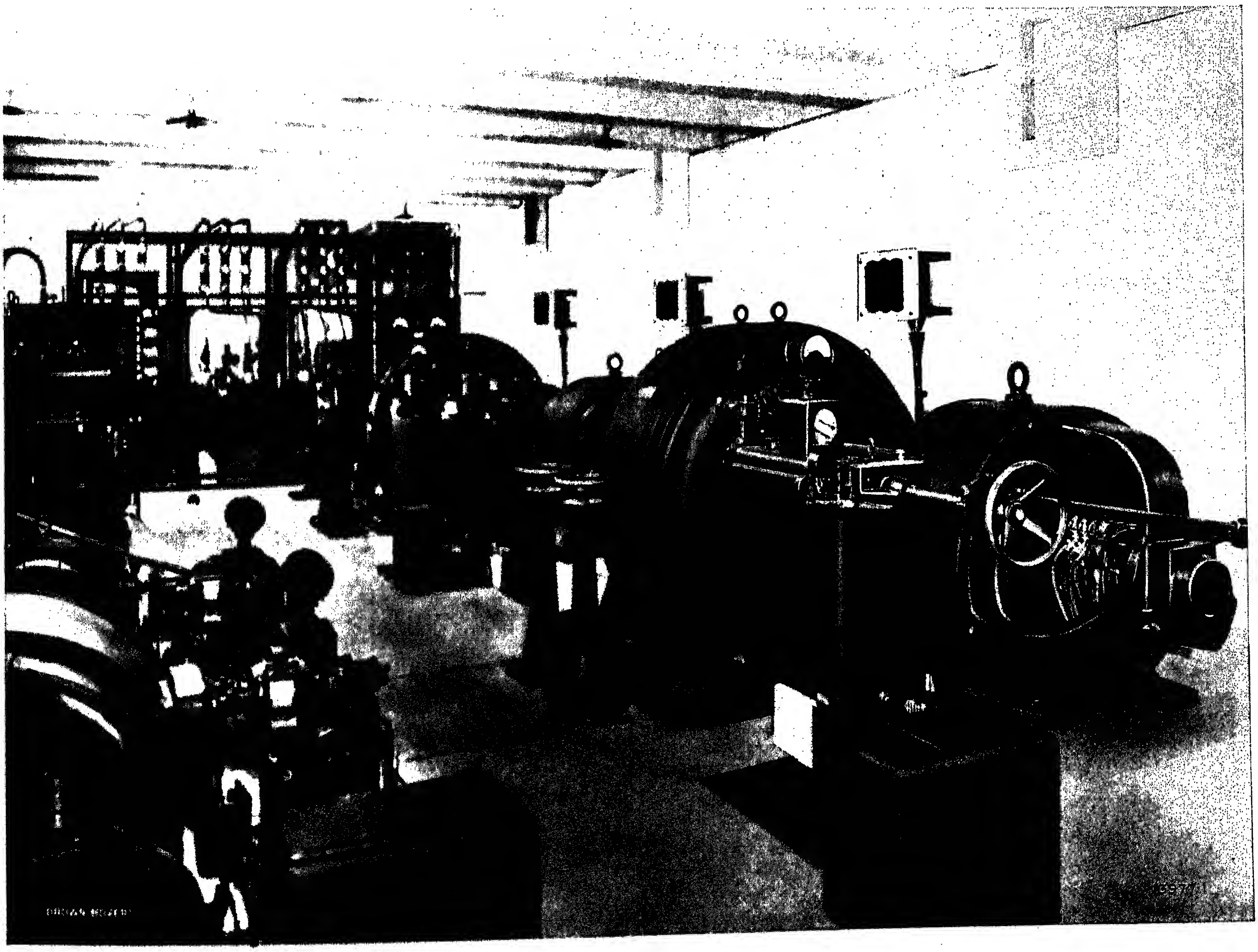
A surge test of similar underlying principles has been introduced in Germany since 1923. Whereas the method of surge testing laid down by the German regulations imitates the effect of making and breaking the circuits on all three phases, however, that standardised in Switzerland resembles a flashover to earth on one phase. Both methods are equally effective.
(MS 317)

S. Rump. (J. R. L.)

VOL. X JUNE, 1923 No. 6

THE BROWN BOVERI REVIEW

EDITED BY BROWN, BOVERI & CO., BADEN (SWITZERLAND)



GENERAL VIEW OF THE MACHINE ROOM IN THE TRANSFORMER TESTING DEPARTMENT OF BROWN, BOVERI & CO., BADEN.

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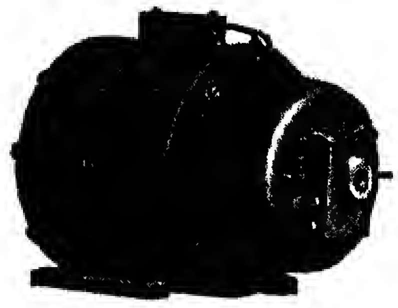
DIRECT-CURRENT MACHINES
FOR SMALL AND MEDIUM OUTPUTS

0·1 to 150 kW.

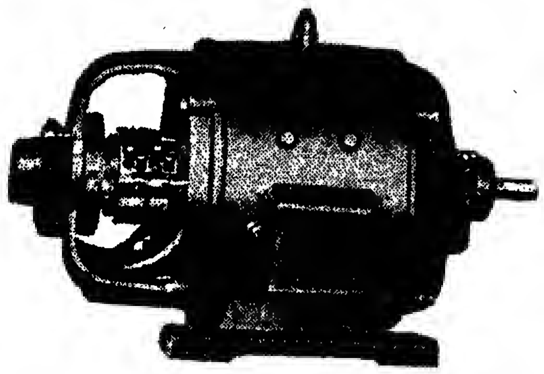
10525-I

Protected machine, Types G 12—22.



10524-II

Totally-enclosed motor, Types G K 12—22.



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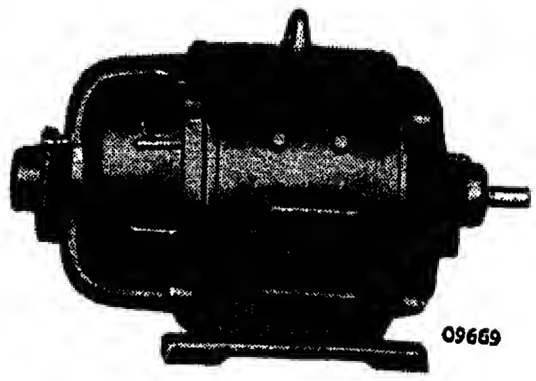
Protected machine, Types G 32—72.



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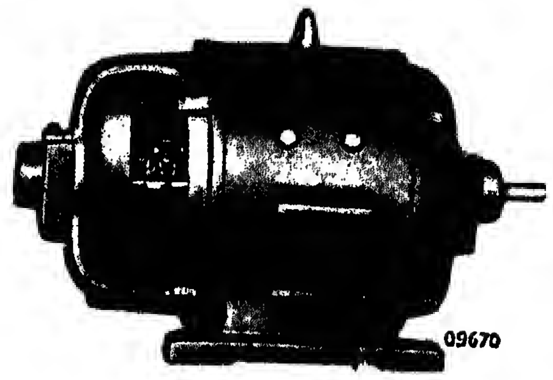
Drip-proof motor, Types G R 32—72. (Aperture in enclosing cover facing downwards.)



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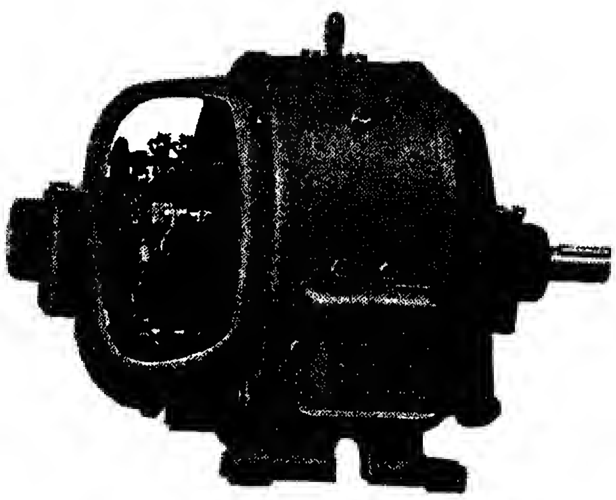
Drip-proof motor, Types G R 32—72. (Aperture in enclosing cover turned upwards for inspection of brushes.)



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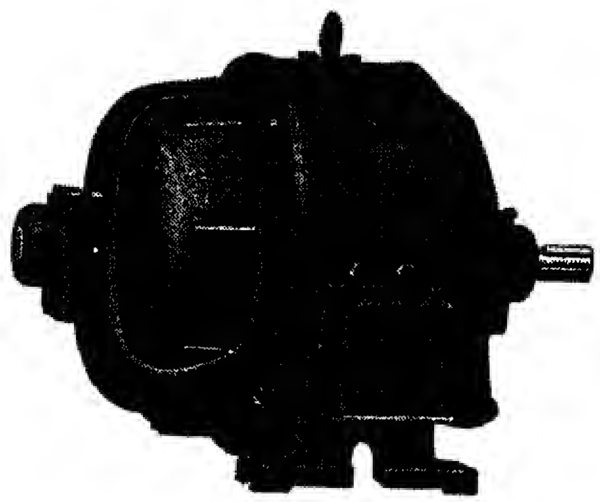
Protected machine, Types G 114—166 a.



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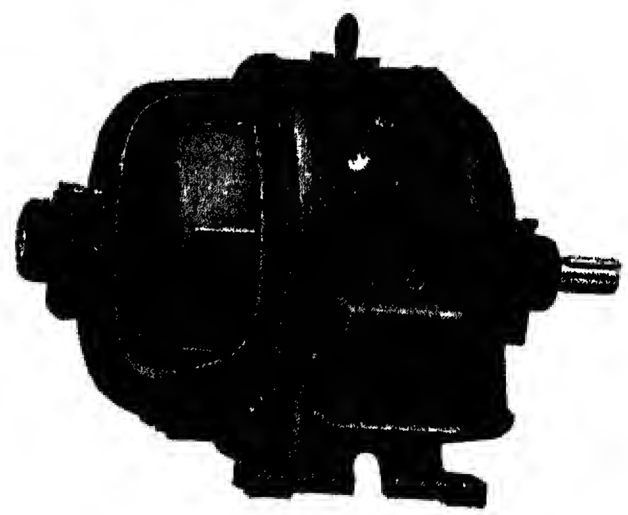
Drip-proof motor, Types G R 114—166 a.



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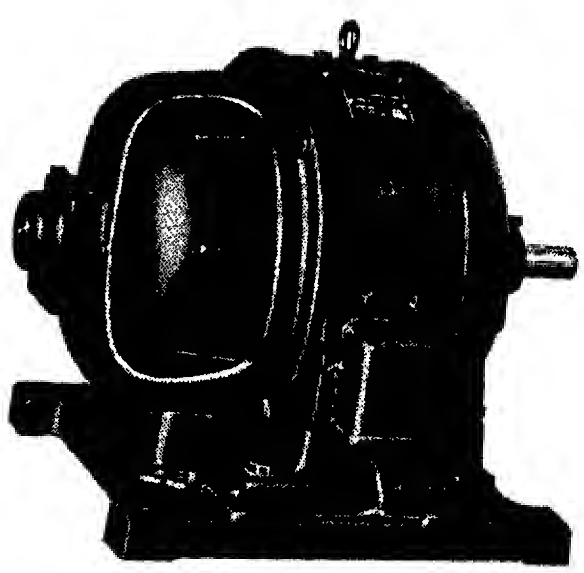
Totally-enclosed motor, Types G K 114–166 a.



09674

Pipe-ventilated motor, Types G D 114—166a.

THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & CO., BADEN (SWITZERLAND)

VOL. X | JUNE, 1923 | No. 6

The Brown Boveri Review is issued monthly. Single numbers: 1.20 francs (1 shilling). Yearly subscription: 12 francs (10 shillings).

THE NEW TRANSFORMER TESTING INSTALLATION IN THE BADEN WORKS OF BROWN, BOVERI & CO.

Decimal index 621.795:621.314.3.

I. Introduction.
II. General arrangement.
III. Machine room and distribution installation.
IV. Testing bay for standard measurements with special instrument tables.
V. Dark room.
VI. Pressure-surge test room.

I. INTRODUCTION.

THE extraordinary development in high-tension power transmission can to a great extent be attributed to the progress that has been made in the manufacture of transformers during recent years. It is only as a result of the high pressures attainable by the use of transformers that long-distance transmission of electricity, and its distribution over wide areas, have become reasonable propositions. Industrial chemistry also owes its immense development largely to the progress made in transformer construction, as chemical factories usually receive their electrical energy under high tension from distant generating stations, and transform it to low pressures with correspondingly heavy currents.

The building of transformers has reached its present stage only by reason of extensive experiment, and long years of study and practical experience. The cooling problem, which until recently has given rise to difficulty, particularly in the case of large transformers, may to-day be regarded as completely solved. The introduction by Brown, Boveri & Co., of their patent short-circuit-proof winding supports has resulted in the production of a type of transformer fully equal to the severe demands placed upon it in the working of large power stations. The firm has always taken an active part in the development of the transformer, frequently leading the way with new improvements. Their transformers stand in the front rank, both as regards the high tensions with which they deal, and the particular soundness of their construction.

The following tables summarise the manner in which the construction of Brown Boveri transformers has developed since the year 1894. Those mentioned in the first table are selected according to their output, and those in the second, according to the magnitude of the pressure.

Largest output of individual transformers.

Year of order	Installation	Output kVA
1894	Vonwiller & Cie., Romagnono	90
1901	Société Franco-Suisse pour l'Industrie Electrique, Geneva	1 150
1905	Eschweiler Bergwerksverein, Kohlscheid	2 500
1910	Nordostschweizerische Kraftwerke (for Löntsch power station)	6 250
1913	Rheinisch-Westfälische Elektrizitätswerke, Essen	23 500
1922	Zentrale Venaus Stà. delle Forze Idrauliche del Moncenesio, Turin	24 000

Highest pressures.

Year of order	Installation	Pressure Volts
1894	Portlandzementfabrik Heilbronn, Heilbronn	5 000
1901	Société Franco-Suisse pour l'Industrie Electrique, Geneva	26 000
1910	Zentralschweizerische Kraftwerke Lucerne (for Arni power station)	45 000
1915	Kraftwerk Laufenburg, A. G., Laufenburg	76 000
1918	Electra de Viesgo, Santander	100 000
1922	Società delle Forze Idrauliche dell'Alto Brembo, Milan	135 300

Up to the end of the financial year 1921-2, Brown, Boveri & Co. had built transformers with an aggregate output of over 10'200'000 kVA.

The continual advances in the output and pressure must be accompanied by a corresponding

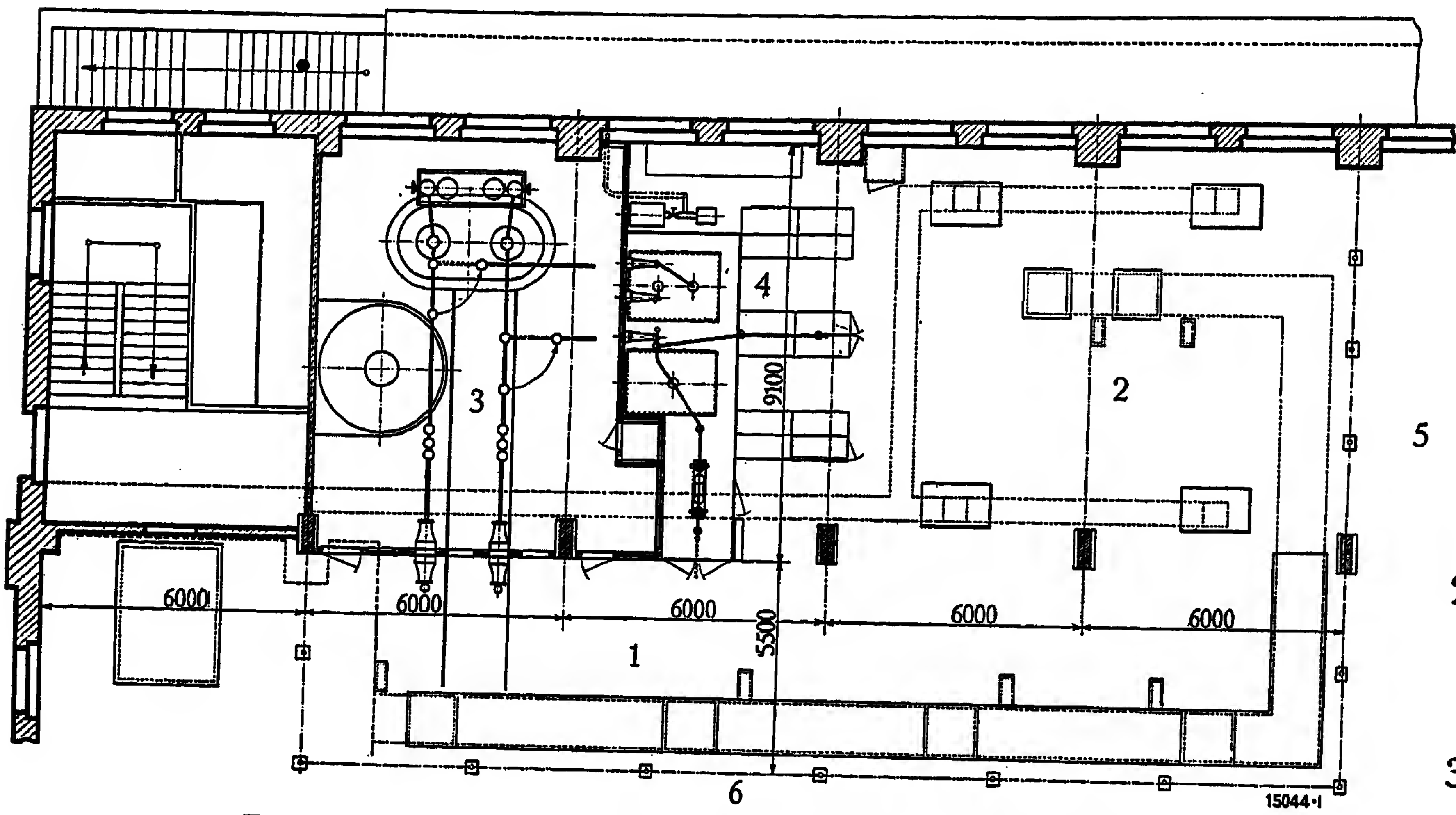


Fig. 1. — Ground plan of the transformer testing department.

1. Section for testing large transformers.
2. Section for testing small transformers.
3. Dark room.
4. Pressure-surge test room.
5. Erection shop for small transformers.
6. Erection shop for large transformers.

In order to make provision for the complete testing of the whole range of transformers manufactured, the testing department was divided as follows:—

1. Section for standard measurements and output tests on large transformers.
2. Section for carrying out similar tests on small transformers.
3. Dark room for testing various insulating materials in air, in oil, and under rain conditions, and also for acceptance tests on large transformers, particularly with respect to insulation.
4. Room for pressure-surge experiments on transformer materials, and in connection with phenomena occurring in practice.

increase in the care given by the manufacturer to testing and research, and a well-arranged testing installation is thus a matter of the greatest importance. When building the new transformer erection shops in the year 1919, the firm decided to install, at the same time, a new transformer testing plant also. This was ready to commence work in 1921 and is described in the present article.

II. GENERAL ARRANGEMENT.

As can be seen from the plan (Fig. 1), the transformer testing department adjoins the erection shops, so that transformers can be conveyed directly from one to the other. For this purpose, high-speed electric cranes of the most recent pattern are installed; that for dealing with large transformers is fitted with separate lifting motions for 5 and 40 tons, while the smaller types are handled by a crane of 8 tons capacity.

The testing department measures 14·6 m × 24 m: that is, a total floor space of 350 m². The various machines with the necessary switchgear and distribution plant, the testing transformers with their induction regulators, and an air condenser are accommodated in the basement (Fig. 3). Here the 4000-V, three-phase current from the Baden town supply is transformed down to 380 V, and led to the driving motors of the several alternating and direct-current generators. For heavier loads, three-phase current is obtained from the alternators in the electrical machine testing department, from the firm's own power station, or, if necessary, from the cantonal power stations, either directly at 8000 V, or at a lower pressure through step-down transformers.

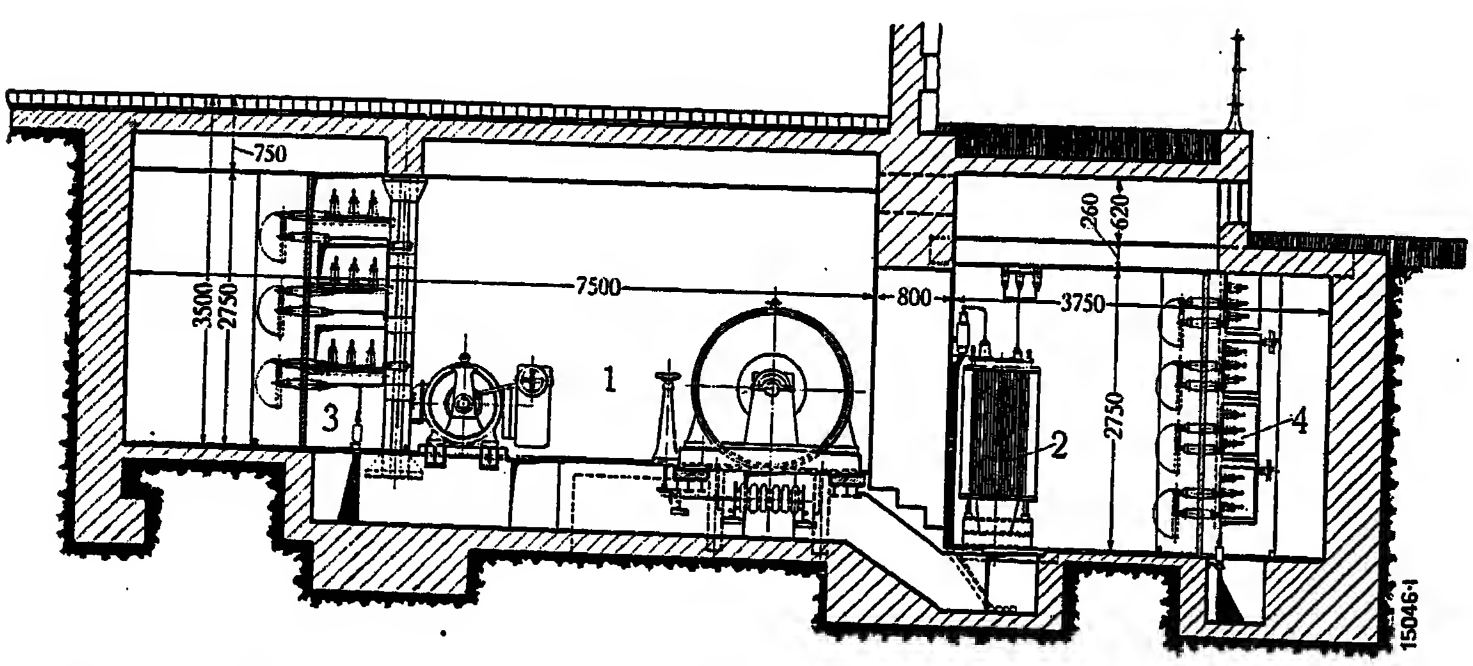


Fig. 2. — Section through the machine room showing the selector boards.

1. Machine room.
2. Step-down transformer, 4000/380 V.
3. Selector board for pressures up to 20'000 V.
4. Selector board for pressures up to 3000 V.

III. MACHINE ROOM AND DISTRIBUTION INSTALLATION.

The most important, as well as the most interesting problem, which had to be dealt with in building the new transformer testing department, was the arrangement of the machine room and distribution installation. It is impossible to do good work with speed and precision unless a sufficient number and variety of machines and a correctly planned distri-

bution system are available. The importance of eliminating, as far as possible, all risk in making measurements during tests, most of which involve high tensions, will be readily understood. It is no less important, however, to be able to carry through the tests quickly and accurately, and with a minimum of trouble. As explained below, the equipment of the machine room has been so planned that both conditions can be fulfilled. A general view of this section of the plant appears on the front cover of the present issue; the portion of the basement containing it measures 15 m × 12 m — an area of 180 m².

The following details can easily be distinguished in Fig. 2:—

1. The machine room proper in the centre.
2. The low-tension selector board with the step-down transformer to the right.
3. The high-tension selector board to the left.

The incoming 12'000-V, three-phase cables, with the oil-switches, can be seen in the frontispiece.

By this arrangement, with the machine room in the centre and the selector boards on either side, the best use is made of the space available, and the leads from the machines to the selector boards are as direct and short as possible. The equipment

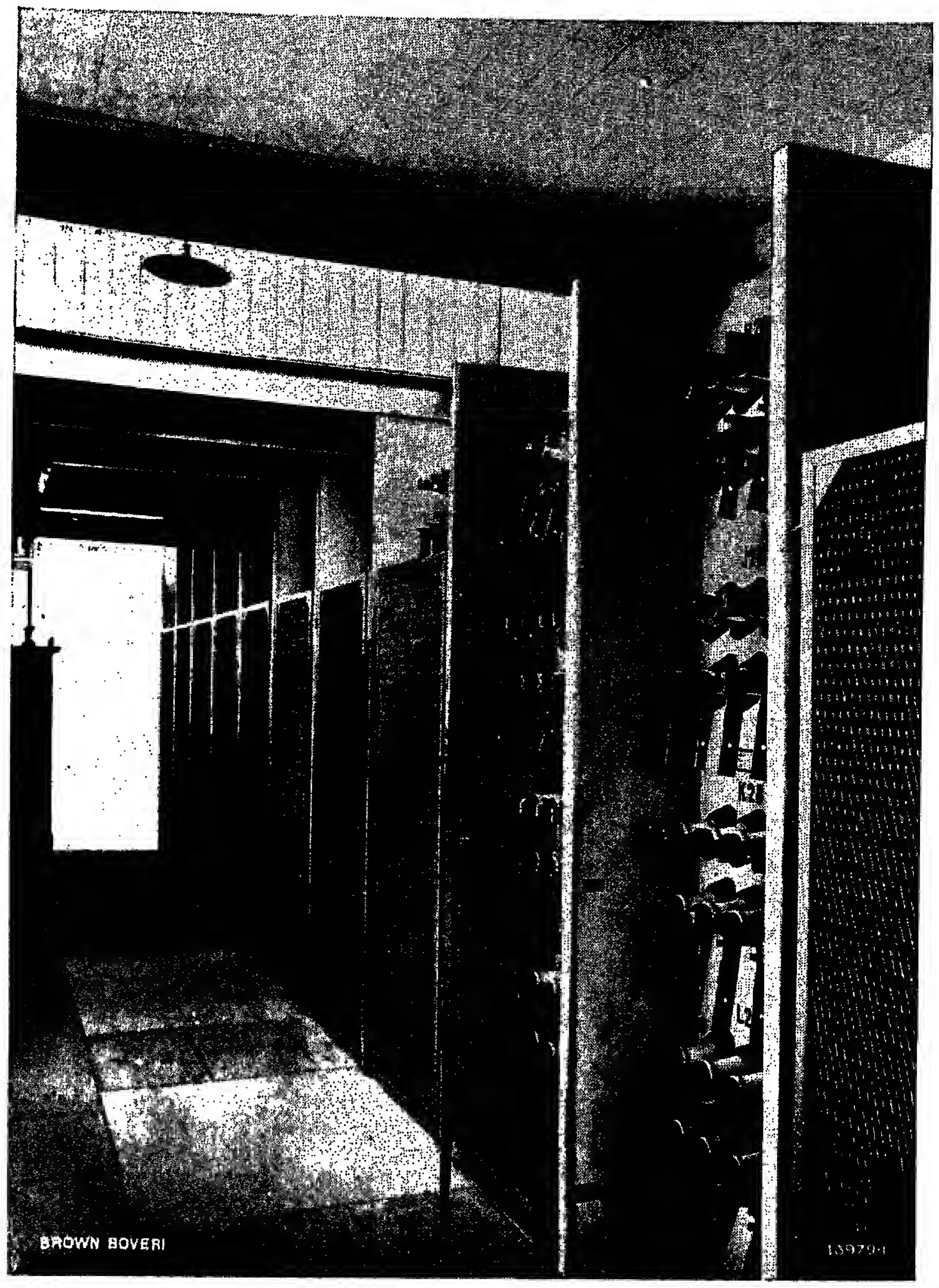


Fig. 4. — The front of the low-tension selector board. (Step-down transformer for 4000/380 V in the background).

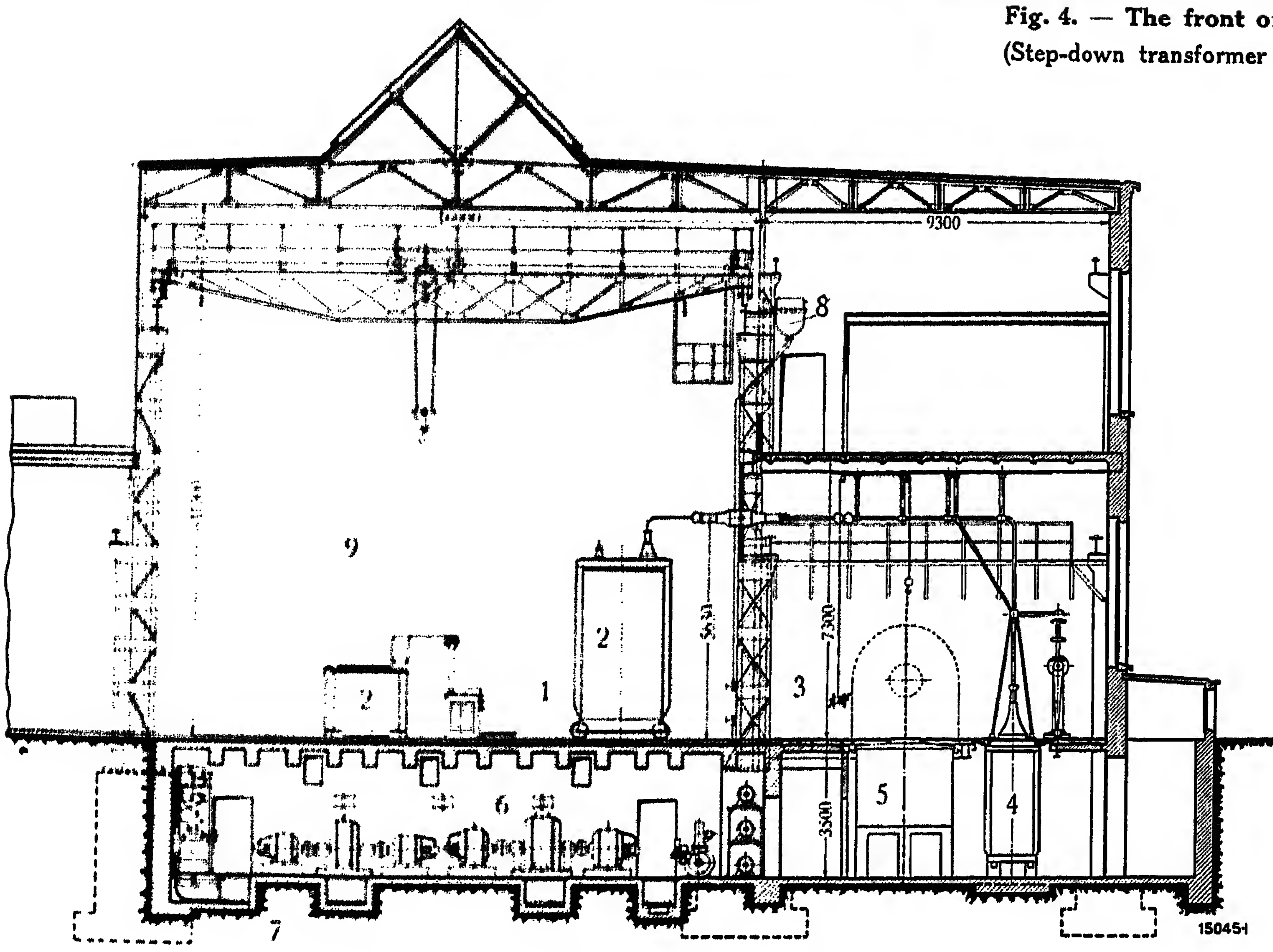


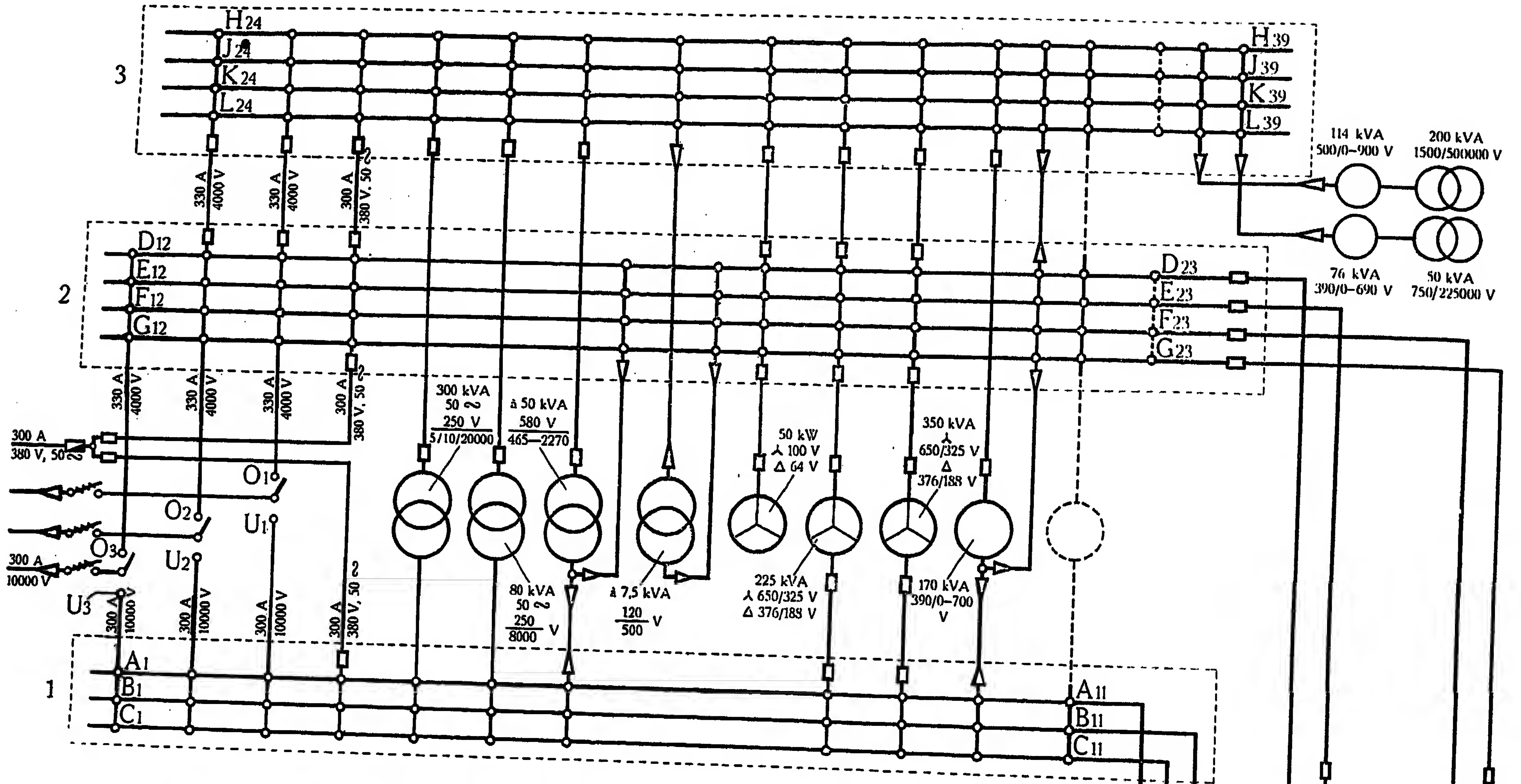
Fig. 3. Section through the transformer testing department.

1. Section for testing large transformers.
2. Apparatus under test.
3. Dark room.
4. Testing transformer for 500 kV.
5. Oil tank.
6. Machine room.
7. Incoming three-phase cable, 400 A at 12'000 V.
8. Water cistern.
9. Erection shop for large transformers.

of the machine room is as follows:—

- 3 three-phase alternators, with outputs of 350, 225, and 150 kVA,
- 1 induction regulator for an output of 190 kVA,
- 2 auto-transformers,
- 2 three-phase transformers.

The alternators are each provided with two driving motors which can be started up by remote control from the testing department proper. Those driving the two smaller alternators run at speeds which correspond to frequencies of 50 and 100 cycles, and those driving the 350-kVA machine, to 40 and 50 cycles. (The



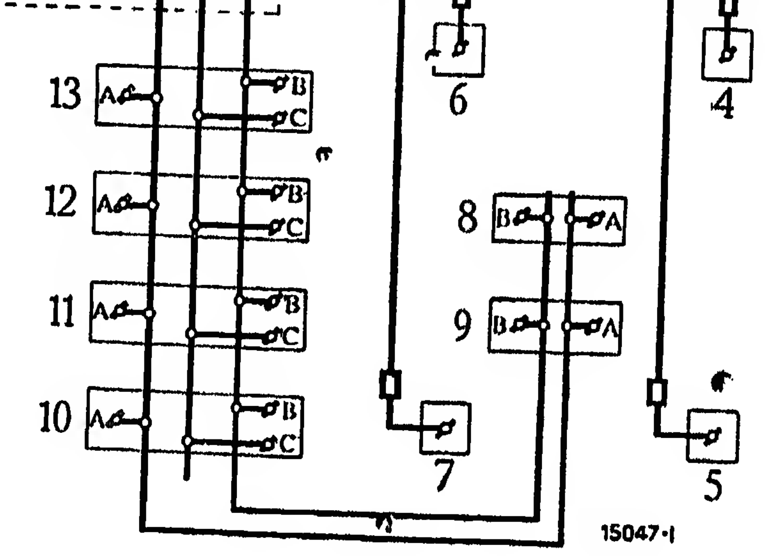


Fig. 5. — Single-pole diagram of machines and distribution installation.

1. Selector board for pressures up to 20'000 V.
2. Selector board for pressures up to 3000 V.
3. Auxiliary selector board.
4—13. Junction points for instrument tables.

frequency of 100 cycles is chiefly used for testing the insulation of transformer windings at twice the rated pressure.)

In order that the alternators may be used to provide a variety of pressures, their phase windings are divided into two symmetrical halves with leads to special switches, by means of which they can be connected in star or delta, series or parallel. The highest line pressure obtainable from the alternators in star-series connection is 750 V. If higher pressures are required, intermediate transformers are used, of which the following may be mentioned: — the three-phase auto-transformers which can be employed for pressures up to 2000 V, an ordinary three-phase transformer for pressures up to 8000 V, and one with tappings on the high-tension winding for 5000, 10'000, and 20'000 V.

As briefly mentioned in Part II, the current necessary for making measurements on large transformers can be obtained from any one of three sources:—

Fig. 6. — A portion of the back of the high-tension selector board.

the 1500-kVA, 50 or 16⅔-cycle alternators in the dynamo and motor testing department, the firm's own turbo-alternator power plant, or the public supply. For this purpose, special three-phase cables are provided, three in number, and each rated for 400 A at 12'000 V. This makes it possible to test even the largest transformers on full inductive load.

Selector boards for both high and low pressures are fitted, the latter being completed by an auxiliary panel. The high-tension selector board can be used up to 20'000 V, and that for low tension with the auxiliary panel up to 3000 V.

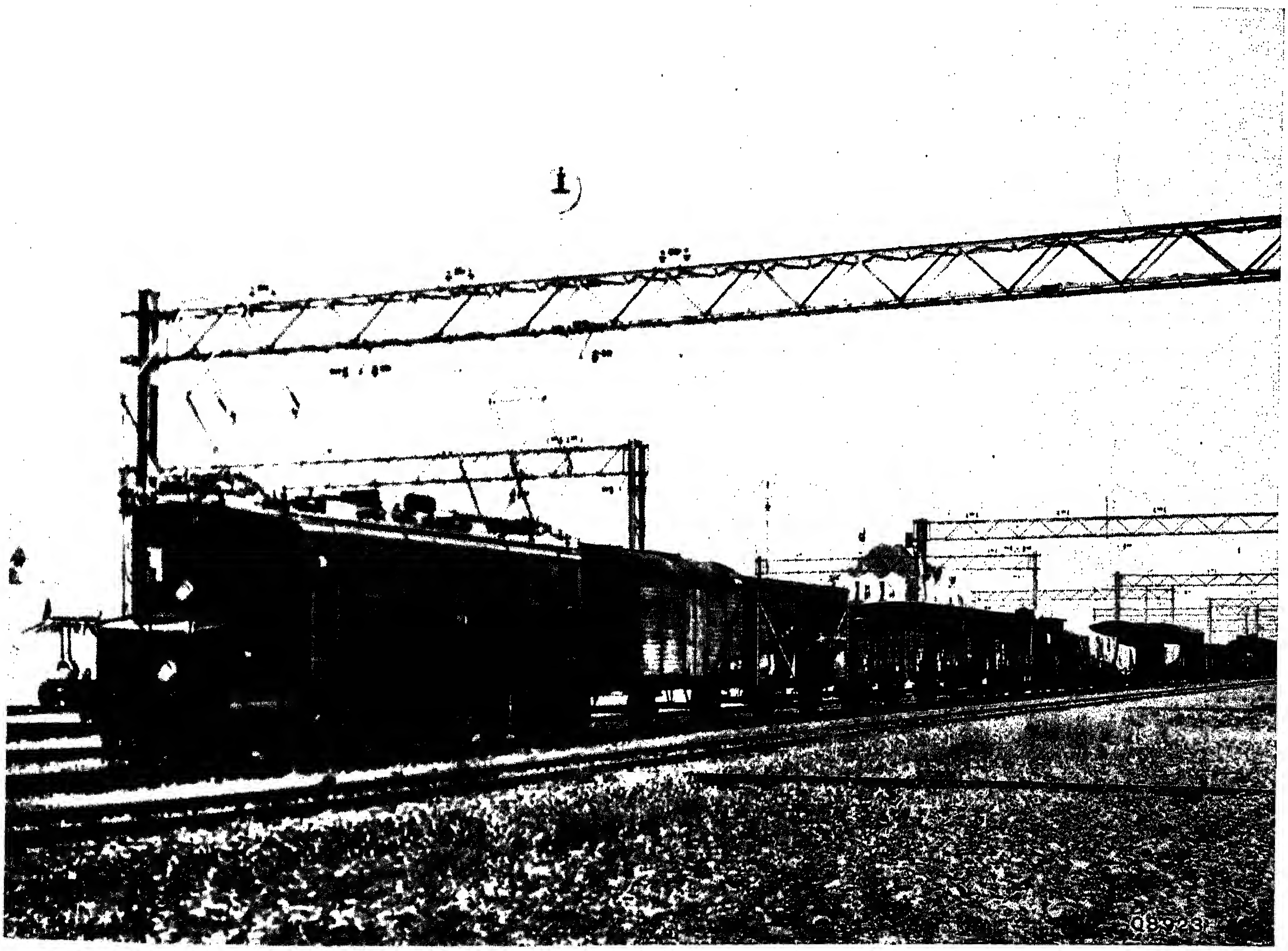
Fig. 4 shows the front of the low-tension selector board with its switches, Fig. 5 the single-pole diagram of connections for the selectors, machines, transformers, incoming cables, and junction points for instrument tables, and Fig. 6 the busbars at the back of the high-tension board. The diagram provides an illustration of the number of different connections it is possible to make, and gives those for the 350-kVA alternator. It will be seen that the machine can be connected direct to the three systems of the high-tension selector board, and to the four systems of both the low-tension and auxiliary boards. In addition, the same alternator can operate through the 300-kVA transformer with the same range of connections.

The machines and transformers are connected, by means of three single-pole knife switches, to the busbars which lead the current to the testing department.

In Part IV some further details of the distribution system will be given with regard to their bearing upon the testing department itself.

Ed. Lienhard. (G. T. S.)

(To be concluded.)



1 B-B 1 locomotive on the Bernese State Railway.

STARTING DIAGRAM OF ELECTRIC TRAINS WITH MOTORS HAVING A SERIES CHARACTERISTIC.

Decimal index 621. 308 : 621. 334. 2.

List of symbols employed.

G = Total weight of the train in tons.

J = Current per motor in amperes.

k = Curve resistance in kg/ton.

M = Total mass of the train $= \frac{G \times 1000}{9{\cdot}81}$ m^{-1} kg sec^2.

M' = Total effective mass of the train; i. e., the actual mass together with the equivalent rotating mass.

p = Acceleration in m/sec^2.

s = Gradient per 1000 (‰)—up grades considered positive in sign, and down grades negative.

T = Adhesion weight in tons.

V = Speed in km/h.

v = Speed in m/sec.

W = Total resistance to motion in kg.

w = Total resistance to motion per ton in kg; i. e., the tractive effort per ton of train weight necessary for acceleration on an inclined, curved track.

w_1 = Running resistance in kg per ton; i. e., the resistance to motion along a straight, level track, given by the sum of the rolling resistance of the wheels on the rails, journal resistance, and wind resistance.

w_s = Grade resistance in kg/ton.

X, Y = Construction lines drawn at distances x and y respectively from the vertical axis; these distances determine the scales of the derived curves.

Z = Total tractive effort, in kg, developed at the tread of the driving wheels at balancing speed.

Z_b = Tractive effort, in kg, necessary for the acceleration of the train at starting.

$Z_a = Z + Z_b$ = Total tractive effort, in kg, developed at the tread of the driving wheels at starting.

λ = Correction factor for M.

μ = Coefficient of friction between wheel and rail.

A. INTRODUCTION — FUNDAMENTAL FORMULÆ.

IN its forward motion along the track, a train encounters a number of resistances, which are overcome by the tractive effort at the tread of the driving wheels. For constant train speed on a straight, level track, the sum of journal resistance, rolling resistance, and wind resistance is given the comprehensive name "*running resistance*" w_1. Of the usual running-resistance formulæ, those of *Frank*, confirmed by the results of numerous experiments, will be used in the present investigation (Fig. 1).

If the track is not level, the "*grade resistance*" w_s must be taken into account. This is positive for up, and negative for down grades, and is expressed in kg per metric ton train weight by the same number as the gradient per 1000; i. e., $w_s = \pm s$ ‰.

The "*curve resistance*" k, overcome by the train when negotiating curves in the track, may be

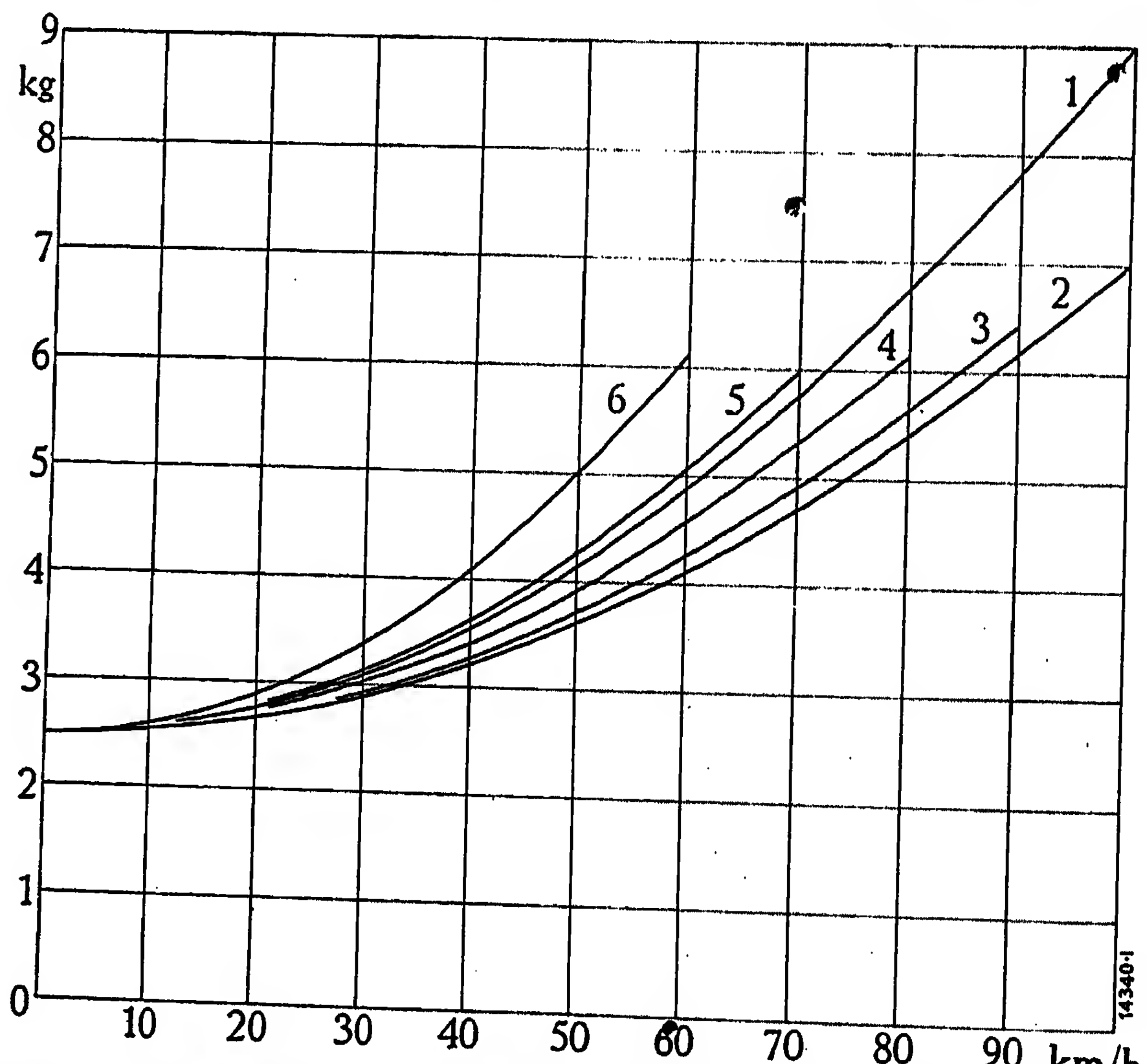


Fig. 1. – Curves of running resistance according to Frank's formulæ.

Ordinates: Running resistance in kg/ton locomotive or train weight.

Abscissæ: Speed in km/h.

Curve 1: $W_1 = 2{\cdot}5 + 0{\cdot}00065\ V^2$; Electric locomotives alone.

Curve 2: $W_1 = 2{\cdot}5 + 0{\cdot}00045\ V^2$; Express trains with bogie coaches.

Curve 3: $W_1 = 2{\cdot}5 + 0{\cdot}00048\ V^2$; Fast trains with about 80% bogie and 20% two-axle coaches.

Curve 4: $W_1 = 2{\cdot}5 + 0{\cdot}00057\ V^2$; Passenger trains with two-axle coaches only.

Curve 5: $W_1 = 2{\cdot}5 + 0{\cdot}0007\ V^2$; Goods trains.

Curve 6: $W_1 = 2{\cdot}5 + 0{\cdot}001\ V^2$; Local and narrow-gauge trains.

Assumption: Still atmospheric conditions.

calculated by the use of the empirical formulæ of *Rœckl* (Fig. 2).

For overcoming the inertia of the stationary mass at starting, or of the uniformly moving mass upon any increase of speed, an extra tractive effort is necessary. This effort overcomes the "*acceleration resistance*", and is proportional to the moving mass and to the acceleration in the direction of motion. So that account may be taken of the influence of the rotating masses (motor armatures, transmission gear, coach wheels, etc.), an equivalent train mass M′, equal to the actual mass M multiplied by a correction factor λ, is employed in the calculations.

The tractive effort Z, developed at balancing speed, is exactly equal to the retarding force W, which is given by the sum of the resistances, so that the following general relation holds good:

$$(W) = Z = G\,(w_1 + s + k) \qquad (1)$$

During starting or increase of speed, the extra tractive effort Z_b, necessary to accelerate the train and the rotating masses in the direction of motion, is given by the expression:

$$Z_b = M\,\lambda\,p = \frac{1000\,G\,\lambda\,p}{9.81} = 102\,G\,\lambda\,p \qquad (2)$$

The exact equation for the total tractive effort at starting is thus:

$$Z_a = Z + Z_b = G\,(w_1 + s + k + 102\,\lambda\,p) \qquad (3)$$

The maximum tractive effort which can be developed at the tread of the wheels without slip is directly proportional to the coefficient of friction μ between the driving wheels and the rails, and to the adhesion weight T of the train. If all possibility of slip is to be excluded:

$$Z_{max} = 1000\,\mu\,T \qquad (4)$$

The coefficient of friction μ falls off with increasing speed (see mean curve Fig. 3).

B. CONSTRUCTION OF THE STARTING DIAGRAM FROM THE SPEED-EFFORT CURVES.

1. *General.*

Given constant gradient and curvature of the track during the period of starting, and neglecting variations in running resistance, s, k and w_1 remain invariable; then from the formula

$$Z_a = G\,(w_1 + s + k + 102\,\lambda\,p)$$

it is evident that, in order to produce a constant starting acceleration p, a constant tractive effort Z_a must be exerted at starting, which in turn implies a constant starting current. In practice, as the motors are started by the controller being moved from contact to contact, it follows that the starting current—and therefore the tractive effort—cannot be kept constant, but both oscillate between maximum and minimum values. On this account, the simplified calculation, based on the assumption of mean constant starting current and tractive effort, provides no accurate conception of the actual loading of the driving motors, the starting time necessary, the distance covered in that time, etc. Further, the acceleration and the efficiency of the motors vary as functions of time, and the running resistance and maximum useful adhesion depend upon the speed. Graphical treatment of the problem by the starting diagram thus provides the clearest means of representing the factors which operate during the starting of trains, and is sufficiently accurate for all practical purposes.

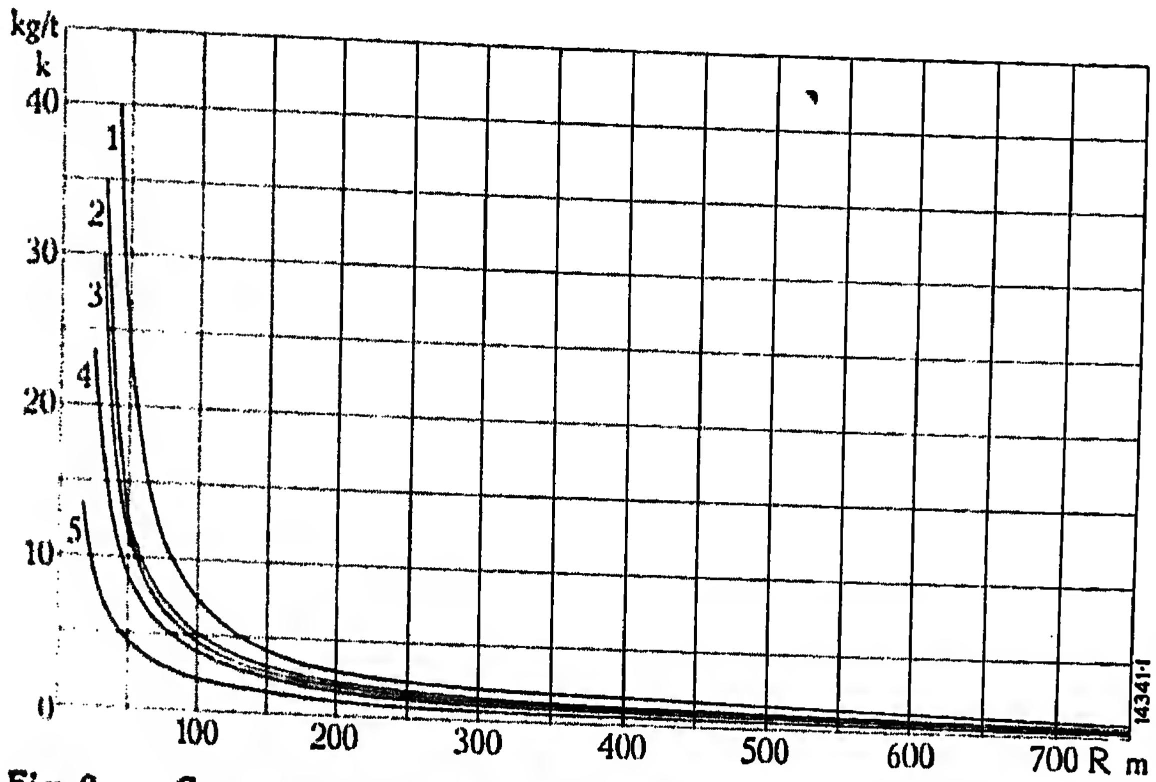


Fig. 2. — Curves plotted according to Rœckl's formulæ for curve resistance.

Ordinates: Curve resistance k in kg/ton.
Abscissæ: Radius of curve R in m.

Curve 1: Gauge 1435 mm;
(1). R > 350 m, $k = \frac{650}{R-55}$ (2). R ≅ 300 m, $k = \frac{530}{R-35}$ (3). R < 250 m, $k = \frac{500}{R-30}$

Curve 2: Gauge 1000 mm; $k = \frac{400}{R-20}$ Curve 4: Gauge 750 mm; $k = \frac{350}{R-10}$

Curve 3: Gauge 900 mm; $k = \frac{380}{R-17}$ Curve 5: Gauge 600 mm; $k = \frac{200}{R-5}$

These values are given on the assumption that the gauge of the rails is suitably increased at the curves. Should this increase in the gauge be lacking or inadequate, a considerable increase in the resistance is involved.

This diagram is based on the characteristics of the motors, and from it the tractive effort, speeds, currents and, if necessary, the efficiency and power factor, can be derived.

2. *The speed-time curve.*

The curve "A" in the diagram is the line of maximum adhesion, constructed on the basis of the curve

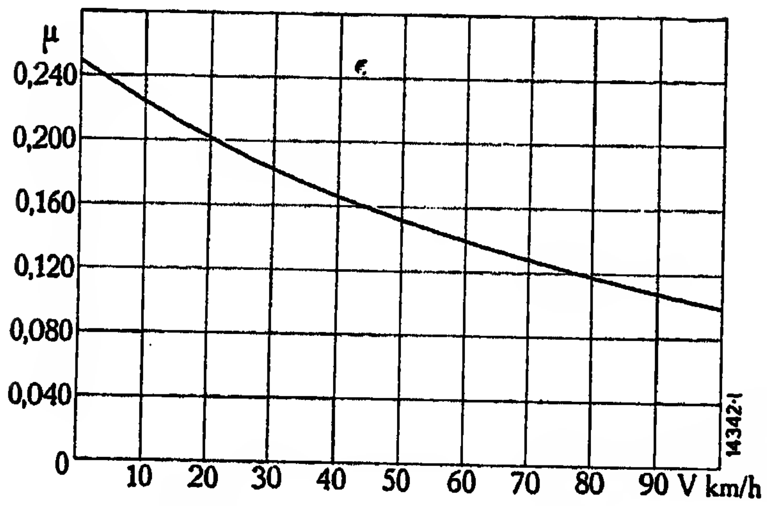


Fig. 3. — Mean value of the coefficient of friction between the driving wheels and track.

Ordinates: Coefficient of friction.
Abscissæ: Speed of train in km/h.

Maximum values at starting:
Without sand, 0·205—0·286.
With sand, 0·5—0·6.

Assumption: Dry and clean rails.

shown in Fig. 3. The resistance curve W represents the total resistance to motion, or the tractive effort Z which corresponds to balancing speed, the two values being identical. The tractive efforts Z_b, available for accelerating the whole train during starting, are given by the differences in the abscissæ of the speed-effort curves, established from the motor characteristics, and the resistance curve W (see Fig. 4).

In order that the curve may be constructed directly, all tractive efforts are to be expressed with reference to the tread of the wheels and as a function of the speed. By a corresponding choice of scales, the $Z_b = f(V)$ curve also represents the acceleration available during starting (formula 2). The scale of the curve p is therefore given by $\frac{\text{effort scale}}{\text{mass}}$.

At the instant when the effort developed becomes equal to the total resistance to motion (the point of intersection S of curves Z_M and W), balancing speed is reached, i. e., given constant track conditions, the train moves uniformly with the speed attained during starting. The accelerating force Z_b, and therefore the acceleration p, diminishes with the increasing speed, and reaches zero for the limiting value of the speed.

The graphical construction for obtaining the speed-time curve from the $Z_b = f(V)$ or $p = f(V)$ curve is as follows:—

From the expression $p = \frac{dV}{dt}$, it follows that $dt = \frac{dV}{p}$, and

$$t = \int_0^V \frac{dV}{p} \tag{5}$$

To carry out the graphical integration, the ordinates of the speed curve are divided into any convenient number of parts n (Fig. 5). Through the points so obtained, parallels to the horizontal axis are drawn, which divide the $p = f(V)$ curve also into a number of zones. If the increments of velocity ΔV are made sufficiently small, it can be assumed that the corresponding mean values of the acceleration $p_m = \frac{p' + p''}{2}$ remain constant. If Δt is the time interval during which the change of speed ΔV takes place, the following expression approximates to formula 5:

$$\Delta t = \frac{\Delta V}{p_m} \tag{5a}$$

The quotient $\frac{\Delta V}{p_m}$ can be considered as the trigonometrical tangent of an angle α, i. e., $\tan \alpha = \frac{\Delta V}{p_m}$. The angles in question are indicated in Fig. 5 on the assumption that p_m = const. in each case. If a straight line X is now drawn parallel to the vertical axis, x units of length from it, the length of the intercept on X made by the arms of each angle α represents $\tan \alpha$, that is, the required interval of time Δt.

If the quantities are represented in the diagram by the following scales:—

Tractive efforts (Z), Retarding forces (W): 1 cm = a kg,
Speeds (V; v): 1 cm = b km/h,
$= \frac{b}{3{\cdot}6}$ m/sec,

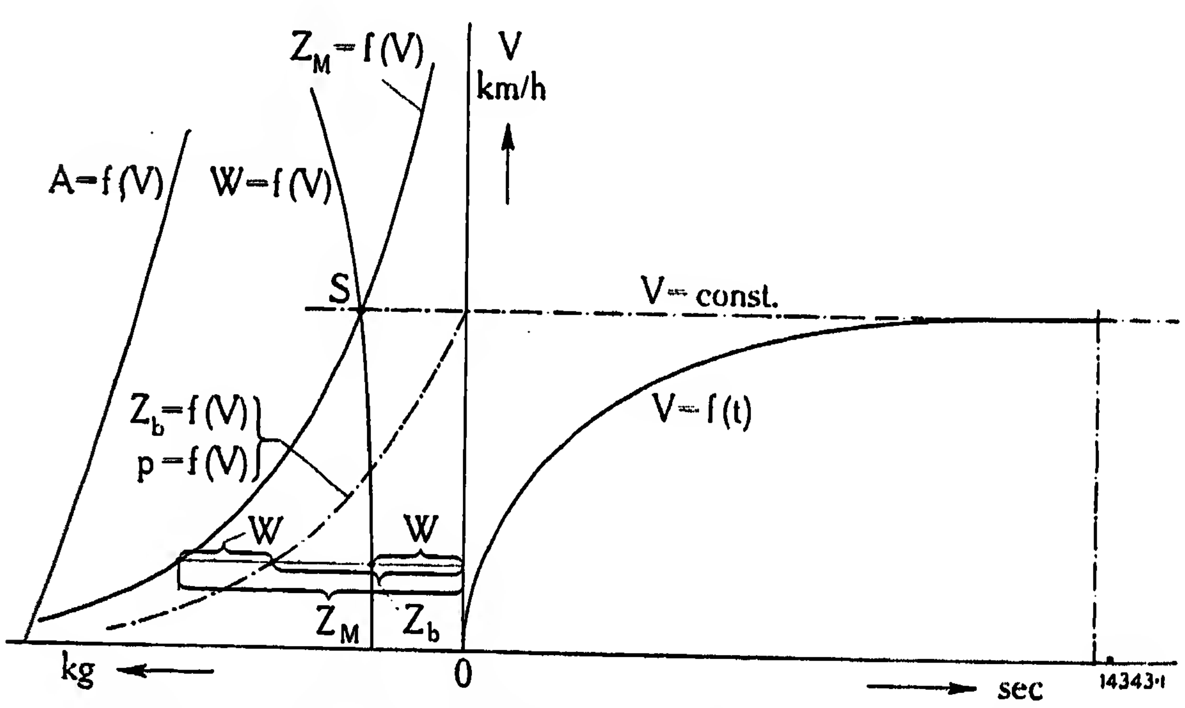


Fig. 4. — Curves from which the diagram is constructed.

Ordinates: Speed of train in km/h.
Abscissæ: Left hand: tractive effort in kg.
Right hand: time of starting in seconds.

Curve A $= f(V)$: Line of maximum adhesion based on Fig. 3.
Curve W $= f(V)$: Total resistance to motion (Formula 1).
Curve $Z_M = f(V)$: Speed-effort curve for a definite pressure at the motor terminals (derived from motor characteristics).
Curve $Z_b = f(V)$: Accelerating force (Formula 2).
Curve p $= f(V)$: Acceleration available at starting.

Time (t): $1\ \text{cm} = \text{c sec}$,
Distance (L): $1\ \text{cm} = \text{e m}$,
Acceleration (p): $1\ \text{cm} = \text{d m/sec}^2$,

the scale of acceleration will be: $1\ \text{cm} = d = \frac{\alpha}{M\lambda}\ \text{m/sec}^2$.

In order that the time intervals Δt may be read directly on the line X, to the scale $1\ \text{cm} = \text{c sec}$, the distance x must be fixed according to:

$$x = \frac{b\ M\ \lambda}{3{\cdot}6\ a\ c}\ \text{cm (or other units of length).}$$

Consider now a new system of coordinates of which the horizontal or time axis is formed by producing the axis of tractive effort to the right. Starting from the origin, set off along this axis the time intervals Δt_1, Δt_2 .... corresponding to the increments of speed, ΔV_1, ΔV_2 .... and determined by the construction described above. The pairs of coordinates (ΔV_1; Δt_1), (ΔV_2; Δt_2) .... fix the points V_1, V_2.... on the required speed-time curve.

3. *The space-time curve.*

If the distance covered by the train during the time t is indicated by L, the instantaneous speed is given by $V = \frac{dL}{dt}$. Let the differentials dL and dt be replaced by ΔL and Δt, these intervals being

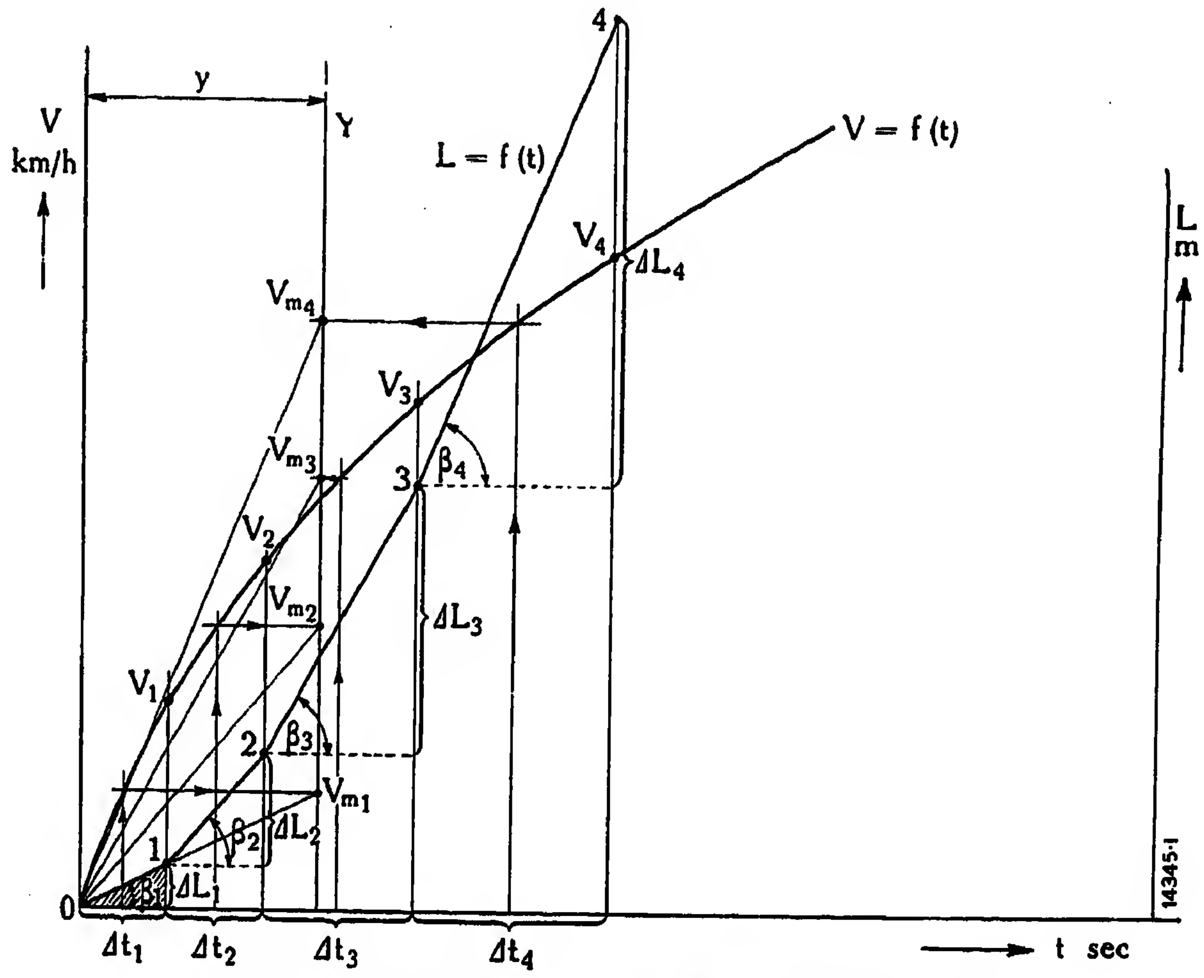


Fig. 6. — Derivation of the space-time curve.
Ordinates: Speed in km/h.
Distance covered in m.
Abscissæ: Time in seconds.

sufficiently small for the mean speed $V_m = \frac{\Delta L}{\Delta t}$ to be considered as constant for the time interval Δt.

Putting $\frac{\Delta L}{\Delta t} = V_m = \tan\beta$, the angles β_1, β_2... which correspond to the time intervals Δt_1, Δt_2... can be found by setting off the mean values of the speed V_{m1}, V_{m2}..., taken from the speed-time curve, on a straight line Y parallel to the vertical axis and distant y from it, and joining the points, so obtained, to the origin (Fig. 6). By means of the angles β_1, β_2..., the required distances ΔL_1, ΔL_2.... can be found from the expression:

$$\Delta L = \Delta t\ y\ \tan\beta.$$

ΔL_1 is obtained directly from the angle β_1 by drawing a perpendicular to the horizontal axis at the point distant Δt_1 from the origin, which gives point No. 1. From point No. 1, a straight line, drawn making an angle β_2 with the horizontal, cuts the ordinate corresponding to the time interval Δt_2 in point No. 2, giving ΔL_2, and so on. The line drawn through these points is the required space-time curve.

4. *The acceleration-time curve.*

As has already been mentioned, the $Z_b = f(V)$ curve, to the scale $\frac{1}{M\lambda}$, gives

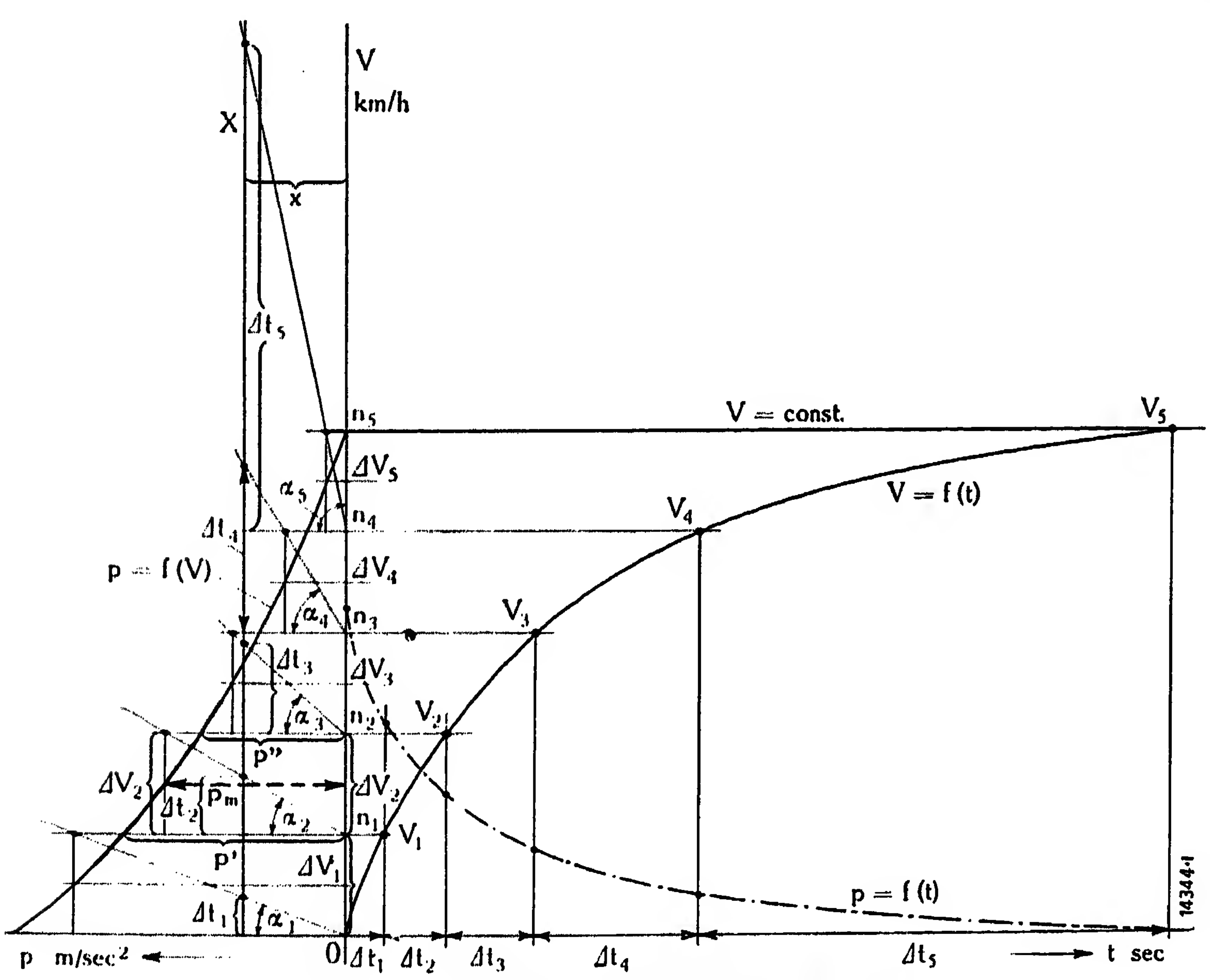


Fig. 5. — Derivation of the speed-time curve.
Curve $p = f(V)$: Available acceleration. Curve $p = f(t)$: Available acceleration.
Curve $V = f(t)$: Speed-time curve.
Scale of $p = \frac{\text{Effort scale}}{\text{Mass}}$.

directly the acceleration corresponding to each value of the speed. Thus the p = f (t) curve can be very simply constructed, as shown in Fig. 5, by setting off the various values of the acceleration p along the ordinates of the corresponding time intervals Δt_1, Δt_2 . . . .

5. *The current-time curve.*

The variation of the current is plotted as a function of the time by obtaining, from the characteristic of the motor, the tractive efforts corresponding to definite speeds and the currents corresponding to these efforts; these values of current, plotted against time, give the curve required. (Each speed taken corresponds to a definite increment of time on the V = f (t) curve.)

The curves of output, efficiency, power-factor, etc., as functions of time, can naturally be constructed in a similar manner.

6. *Example of the construction of a complete diagram* (Fig. 7).

The construction of a complete diagram will now be dealt with, a numerical example being employed, and further explanation of the subject will be given as occasion arises.

As a result of the regulation of the driving motors in steps, the starting diagram is not based upon a single speed-effort curve, as assumed in the foregoing constructions, but upon a series of curves, more or less numerous depending upon the case considered. Consequently the curve giving the tractive effort at starting is of stepped form. The switching over from one step to the next occurs practically without alteration of speed, and is indicated in the diagram by lines parallel to the horizontal axis.

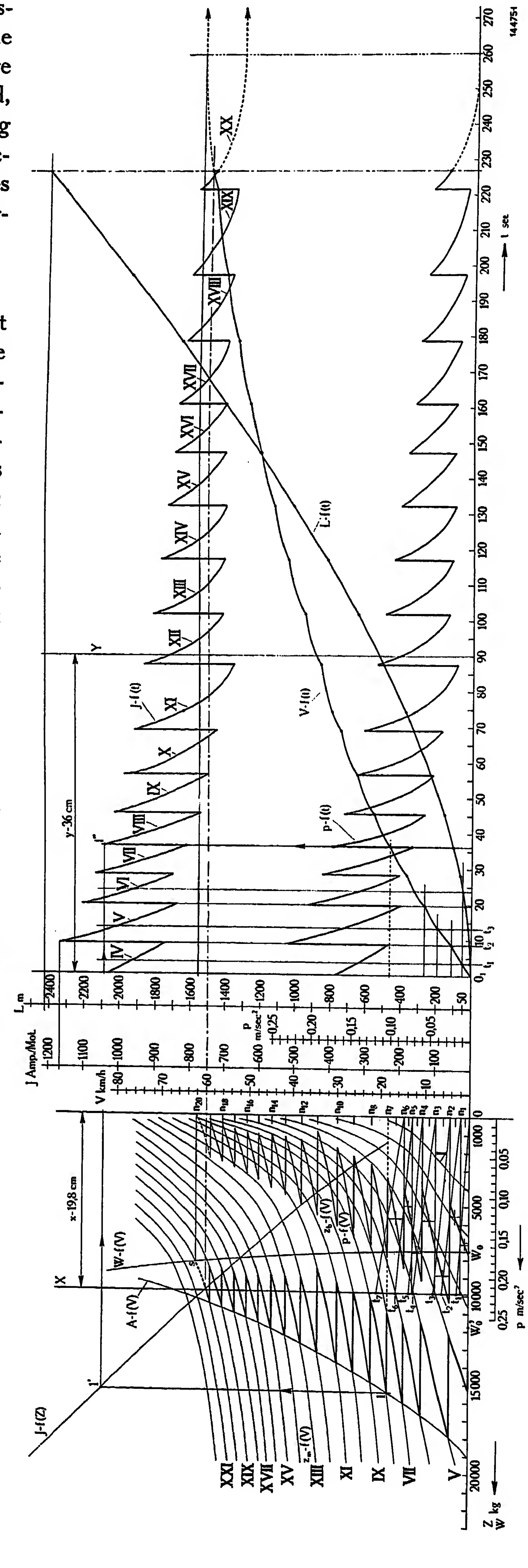


Fig. 7. — Starting diagram of an express train weighing 406 tons, on a gradient of 16 ‰.

Ordinates: Speed in km/h.
Acceleration in km/sec².
Current per motor in amperes.
Distance covered during starting, in m.

Abscissæ: Tractive effort and resistance to motion, in kg, referred to the tread of the driving wheels.
Acceleration in m/sec².
Time in seconds.

Data:
Adhesive weight of the locomotive . . . 76 tons
Weight on the guiding axles of the loco. 30 tons
Weight of the locomotive in working order 106 tons
Weight hauled by the locomotive . . . 300 tons
Total weight of train . . . . . 406 tons

Data:
Total mass of train . . M = 41'400 m^{-1} kg sec².
Total effective mass of train to be accelerated $M\lambda$ = 44'760 m^{-1} kg sec².

Scales:
Tractive effort . . . 1 cm = a = 500 kg.
Speed . . . 1 cm = b = 2 km/h.
Time . . . 1 cm = c = 2·5 sec.
Distance . . . 1 cm = e = 50 m.
Current . . . 1 cm = 25 A.

Distance $x = \frac{b\,M\,\lambda}{3{\cdot}6\;a\;c} = 19{\cdot}8$ cm.

Distance $y = \frac{3{\cdot}6\;e}{b\;c} = 36$ cm.

Results obtained from the diagram:
Curves: V = f (t), p = f (t), J = f (t), L = f (t).

For a final speed V_e = 60 km/h:
Starting time . . . . . . = 227 sec
Starting distance . . . . . = 2420 m.
Mean acceleration during starting $= \frac{60}{3{\cdot}6 \times 227} = 0{\cdot}074$ m/sec².

Under the above conditions, the train considered reaches balancing speed at 62·2 km/h.

Should the motor characteristics be given in terms of the current, they must first be redrawn—the speed and the motor current being given as functions of the total tractive effort.

If the conditions fixed by the temperature rise of the driving motors permit a full use of the adhesion, the diagram is so constructed that all the peaks of the tractive effort curves lie on the line of maximum adhesion A. If, in special cases, this is impossible without overloading the driving motors, the ordinate must be drawn at that value of the tractive effort which corresponds to the allowable maximum of the current, and this straight line must be regarded as the limit for the peaks of the tractive-effort curves during starting, until the value is reached where it meets the adhesion line.

When the driver has arrived at a notch of the controller giving a value of tractive effort which lies to the left of the point W_o on the curve of resistance to motion, theoretically the train would be expected to start. Practice shows, however, that the resistance experienced in passing from rest to motion (i. e., for $V = 0$) has a considerably greater value than that given by the formula $W = G\,(w_1 \pm s + k)$, on account of the increased journal resistance of stationary trains occasioned by the squeezing out of the oil film at the bearings. Tests made by *V. Glinski*[1] showed that this resistance becomes very much higher, the longer the time during which the train is at rest. The resistance line W is not perpendicular to the horizontal axis at its commencement, but curves strongly towards a point W_o'. As, however, this higher value of the resistance decreases to normal after the first few metres have been covered, this is not shown in the diagram. On the other hand, the first step of the controller should be chosen with regard to this fact, so that starting is sure to take place.

Starting conditions.

A 1 B-B 1 locomotive is to start a train weighing 300 tons (excluding the locomotive) on a 16 ‰ incline, and bring it to a speed of 60 km per hour in the shortest possible time. The starting time and the distance traversed during this period are to be determined, as well as the curves $V = f\,(t)$, $p = f\,(t)$, $J = f\,(t)$, and $L = f\,(t)$.

[1] Zeitschrift des Vereins deutscher Ingenieure (V. D. I.), 1912, p. 2065. It was established experimentally that the starting resistance of run-in electric locomotives with jackshaft and side-rod drive has a mean value of about 30 kg per ton, and that of waggons and passenger coaches, about 12 kg per ton.

Data:

1. *Weight of locomotive* (1B-B1 type) = 106 tons
   Total weight on driving wheels (4 × 19) = 76 „
2. *Weight hauled* (express passenger train):
   6 four-axle coaches, each 42 tons fully loaded . . . . = 252 „
   2 two-axle coaches, each 24 tons fully loaded . . . . = 48 „
   300 tons
3. *Total train weight* (106 + 300) = 406 „
4. *Motor characteristics* (speed and current curves) with reference to the total tractive effort at the tread of the wheels.
5. *Resistance line* $W = f\,(V)$ according to formula (1) for $k = 0$.
6. *Curve of maximum adhesion* "A" according to Fig. 3.

Assumptions:

Scales:

Tractive effort:	1 cm = a =	500 kg.
Speed:	1 cm = b =	2 km/h.
	=	$\frac{2}{3 \cdot 6}$ m/sec.
Time:	1 cm = c =	2·5 sec.
Distance:	1 cm = e =	50 m.
Current:	1 cm =	25 A.

Calculations:

Influence of the rotating masses:

1. Actual mass of the locomotive $= \frac{106 \times 1000}{9 \cdot 81} = 10'800\ m^{-1}\ kg\ sec^2$.
   Equivalent mass of the rotating parts referred to the tread of the wheels $= 1960\ m^{-1}\ kg\ sec^2$.
   Effective locomotive mass to be accelerated $= 12'760\ m^{-1}\ kg\ sec^2$.
   Equivalent rotating mass as a percentage of the mass of the locomotive $= \frac{1960 \times 100}{10'800} = 18\,\%$ $(\lambda = 1 \cdot 18)$
2. Actual mass behind the locomotive $= \frac{300 \times 1000}{9 \cdot 81}$ $= 30'600\ m^{-1}\ kg\ sec^2$.

Equivalent mass of all the coach wheels $= 1400 \text{ m}^{-1} \text{ kg sec}^2$.

Effective mass behind the locomotive to be accelerated $= 32'000 \text{ m}^{-1} \text{ kg sec}^2$.

Equivalent rotating mass as a percentage of the mass behind the locomotive $= \frac{1400 \times 100}{30'600} = 4{\cdot}5\,\%$ $(\lambda = 1{\cdot}045)$

3. Total mass of train $= \frac{406 \times 1000}{9{\cdot}81}$
$= 41'400 \text{ m}^{-1} \text{ kg sec}^2$.

Total equivalent mass of rotating parts $= (1960 + 1400)$
$= 3360 \text{ m}^{-1} \text{ kg sec}^2$.

Total effective train mass to be accelerated $(M\lambda) = 44'760 \text{ m}^{-1} \text{ kg sec}^2$.

Total equivalent rotating mass as a percentage of the total train mass $= \frac{3360 \times 100}{41'400} = 8{\cdot}1\,\%$ $(\lambda = 1{\cdot}081)$

Values for the construction of the diagram:

Scale of the acceleration curve:

$$1 \text{ cm} = \frac{a}{M\lambda} = \frac{500}{44'760} = 0{\cdot}0111 \text{ m/sec}^2$$

or $9 \text{ mm} = 0{\cdot}01 \text{ m/sec}^2$.

$$\text{Distance } x = \frac{b\,M\,\lambda}{3{\cdot}6\,a\,c} = \frac{2 \times 44'760}{3{\cdot}6 \times 500 \times 2{\cdot}5} = 19{\cdot}8 \text{ cm}.$$

$$\text{Distance } y = \frac{3{\cdot}6\,e}{b\,c} = \frac{3{\cdot}6 \times 50}{2 \times 2{\cdot}5} = 36 \text{ cm}.$$

Results obtained from the diagram:

1. Curves $V = f(t)$; $p = f(t)$; $J = f(t)$; $L = f(t)$.
2. Minimum starting time for $V_e = 60$ km/h: about 227 sec.
3. Minimum starting distance for $V_e = 60$ km/h: about 2420 m.
4. Maximum current per motor: about 1168 A.
5. Average acceleration obtained:

$$\frac{V_e}{t} = \frac{60}{3{\cdot}6 \times 227} = 0{\cdot}074 \text{ m/sec}^2.$$

CONCLUSION AND REMARKS.

The starting diagram shows that, with the 22 controller steps provided and under the conditions of adhesion assumed, a 406-ton train can be brought up to a speed of 60 km per hour on a gradient of 16 ‰ in just under four minutes, the average acceleration being $0{\cdot}074 \text{ m/sec}^2$.

It is naturally important, in practice, for the driver to excercise his skill to approach these values as closely as possible. The diagram represents, in a certain sense, the ideal, which can never be exceeded by actual values. However, if the driver operates the controller correctly, so that he approximates closely to the values indicated in the $J = f(t)$ curve, for the intervals of time between switching from one notch to the next and for the maximum current in each case, the result attained will be quite satisfactory.

Mention should be made of the fact that when direct current is employed, distortion of the current-time curve occurs as a result of the

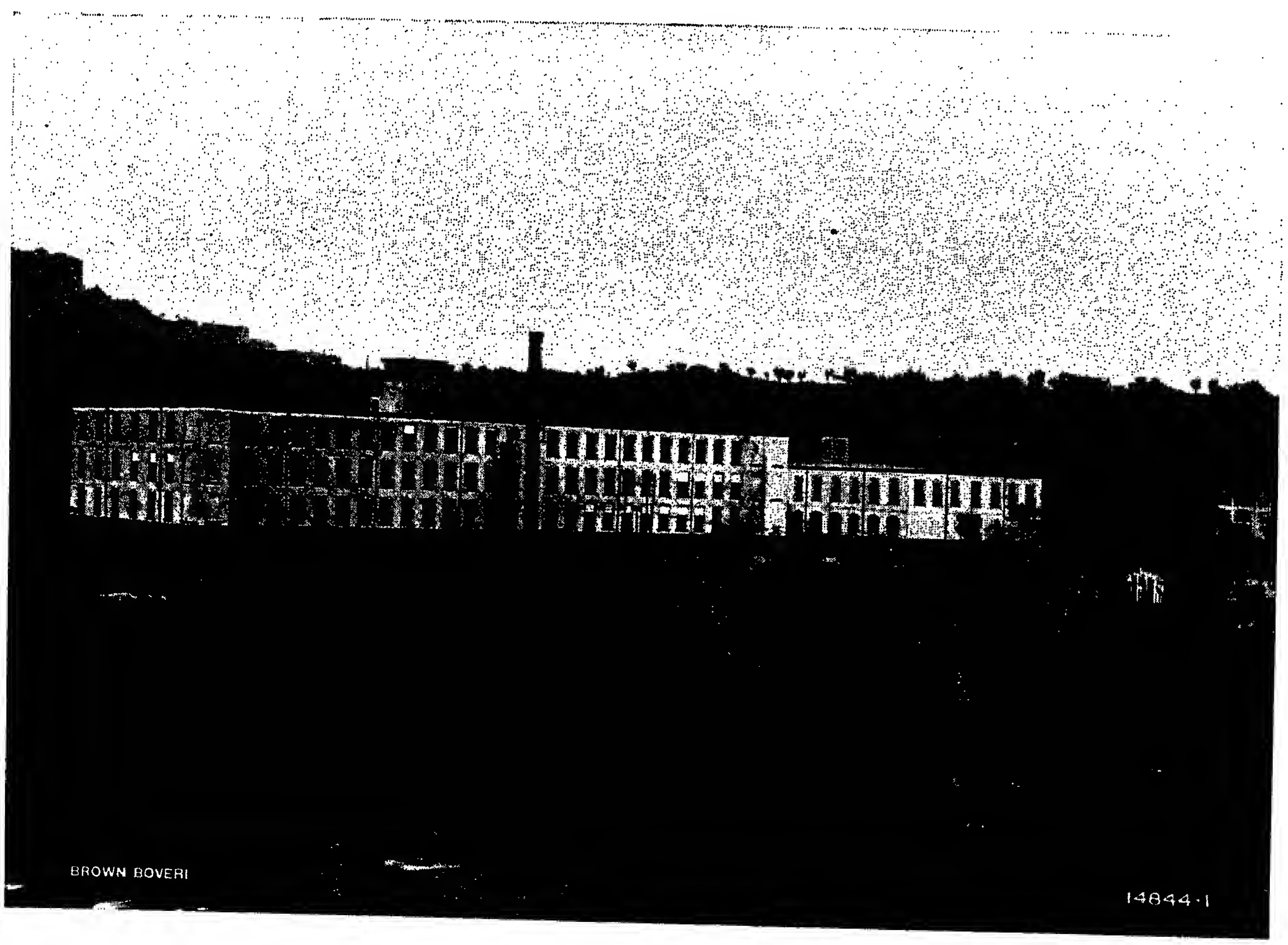


Fig. 1. — The spinning mill of Niggeler & Kupfer S. A. at Capriolo (Italy).

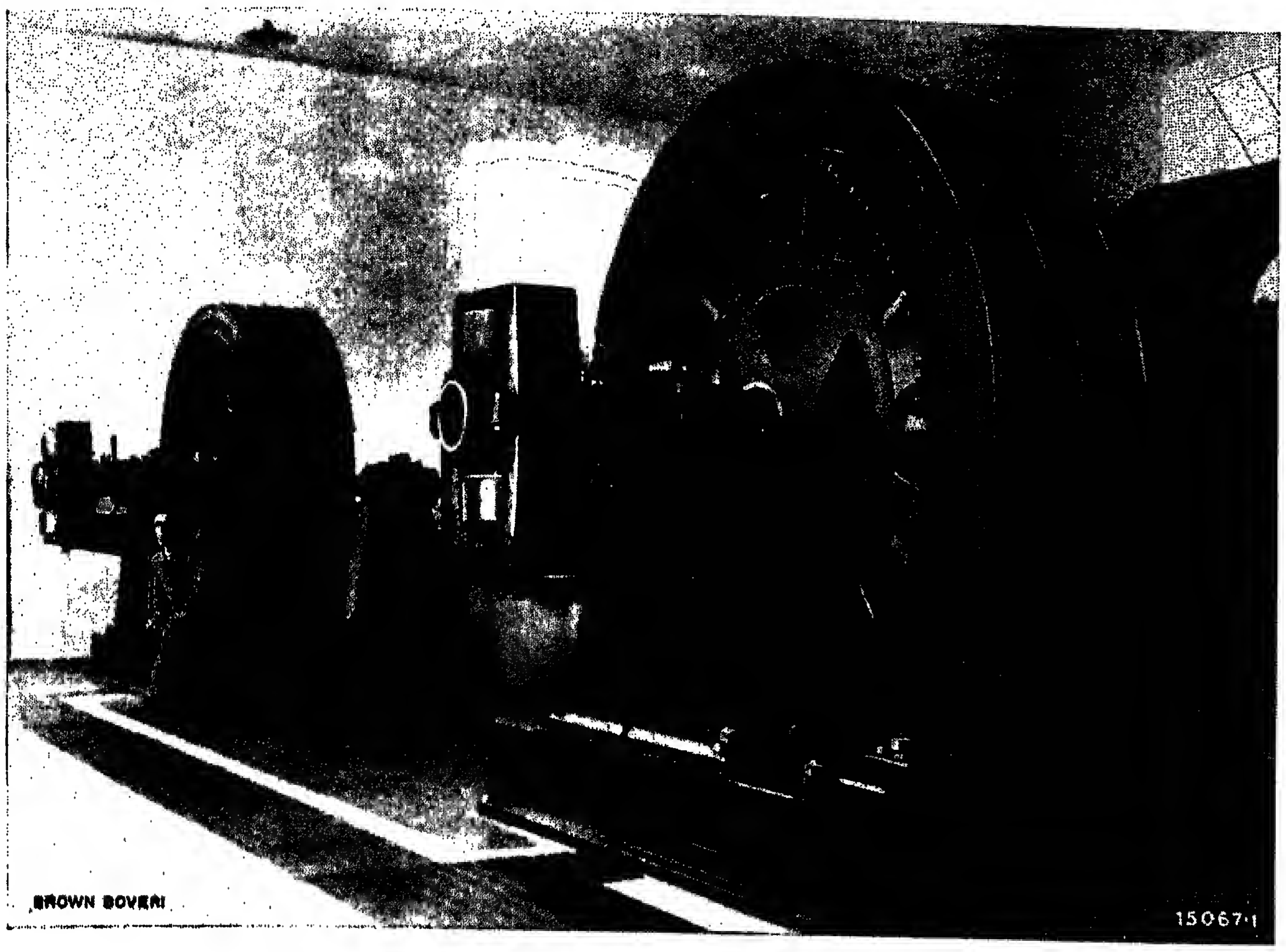


Fig. 2. — Power station in the spinning mill at Capriolo.

self-induction of the driving motors and their circuits. This occasions a lagging of the current, which only rises to its maximum some time after contact is made; consequently the full tractive effort at each step is not available from the first moment. This naturally influences the curve of accelerating force and those derived from it, so that the actual values reached are generally somewhat below those obtained from the diagram.

Finally, it is to be noted that the starting diagram can be used to advantage in electric traction to determine the graduation of controller steps. For this purpose, the peaks of tractive effort, and therefore of acceleration and of current, are based on the diagram only, and the speed-effort curve is arranged accordingly.

Two cases have to be considered: the whole train starting against the most severe conditions to be encountered and the smooth acceleration of the locomotive alone.

A. E. Muller. (G. T. S.)

NOTES.

Reliability of Brown-Boveri plant in spinning mills.

Decimal index 621.39:677.

EQUAL importance is attached in spinning mills to reliability in service and long life of the electrical machinery as to its high efficiency. Reduced upkeep, together with the necessity of writing off only a small portion of the initial outlay, contributes greatly to bring down the total operating expenses.

A striking example, which confirms the above statement, is afforded by the electric generators and motors supplied by Brown, Boveri & Co. in 1895 to the Filatura e Tessitura di Cotone, Niggeler e Kupfer S. A. for their spinning mill at Capriolo in Italy (Figs. 1 and 2).

The machines in question have qeen in service for 27 years, during 15 of which they were actually working day and night, and not once in all this long time have they given the slightest trouble.

In this mill, nearly always the same counts are spun, as is usual also in English practice. The motors are coupled directly to the line shaft. Their arrangement in cabins in the centre of the building (Fig. 3), so that they are easily got at, corresponds to the best present-day practice for group drives. The large three-phase motors, constructed according to C.E.L. Brown's patents, are amongst the first supplied by Brown, Boveri & Co. for being coupled directly to the line shafting in a spinning mill, and they still operate just as satisfactorily as when they were first delivered. This confirms that the great confidence placed in Brown Boveri plant even at that early date was amply justified.

W. Foster. (D. M.).

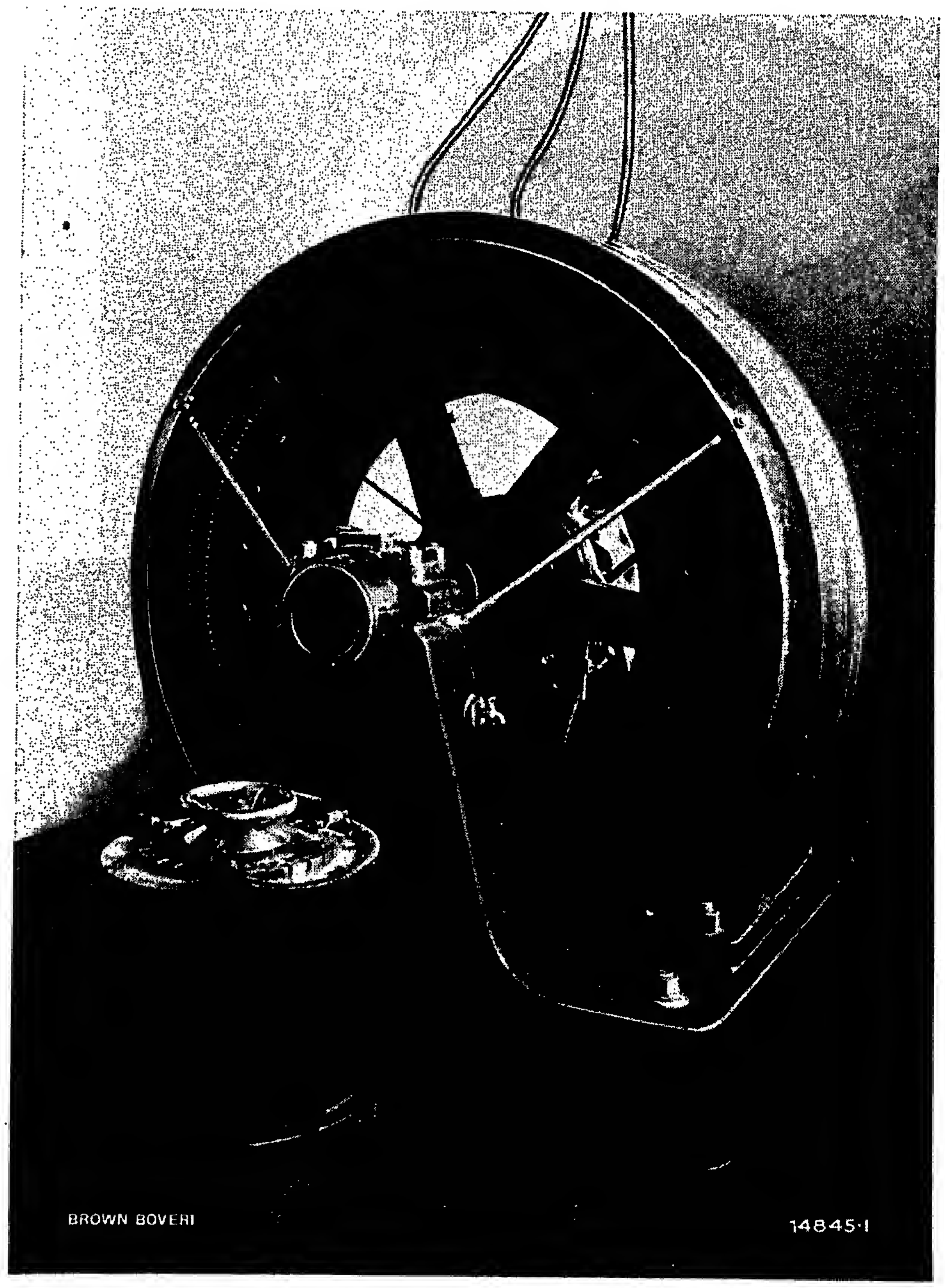


Fig. 3. — 150-H. P., 230-r. p. m. motor for group drive in the spinning mill at Capriolo.

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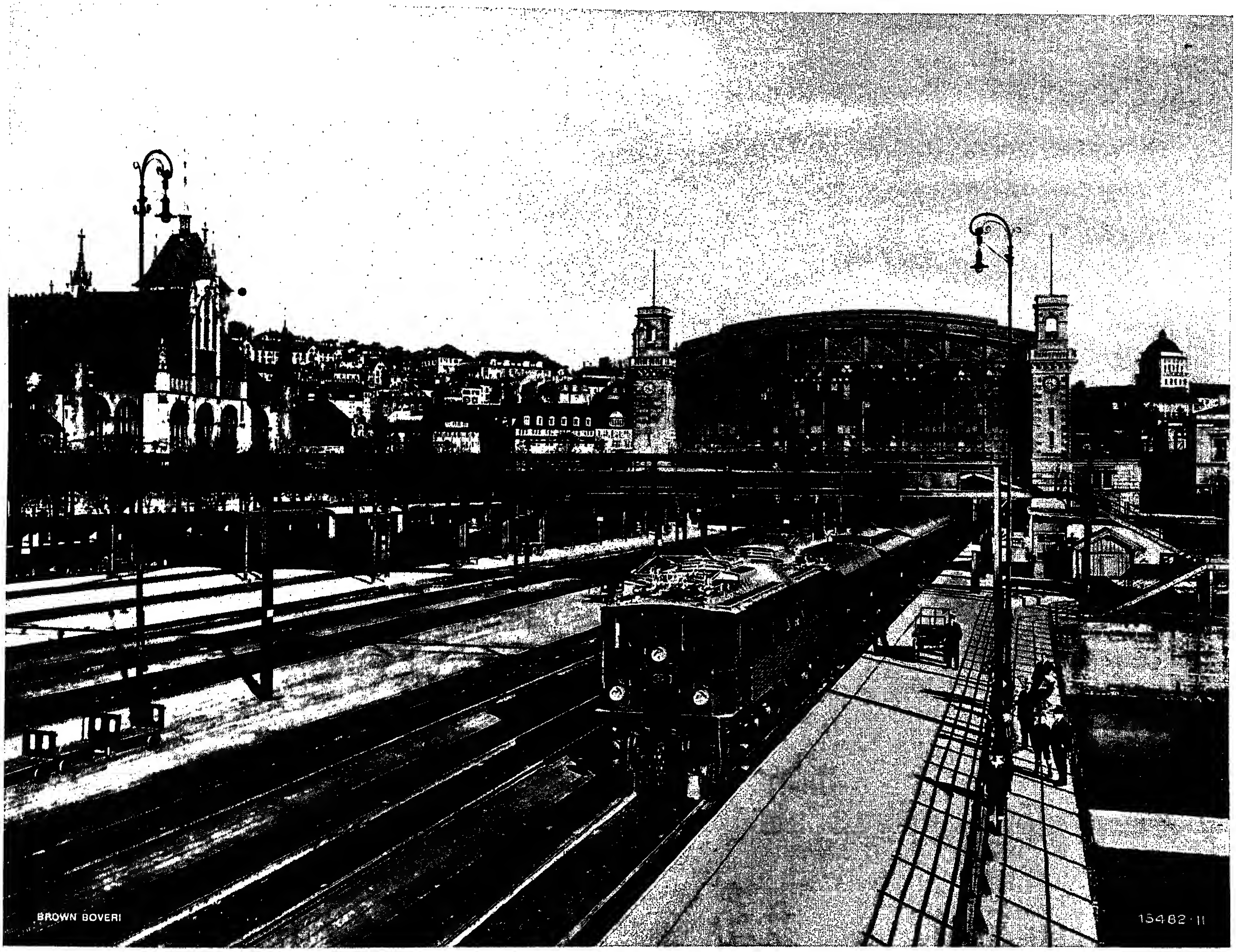
THE BROWN BOVERI REVIEW

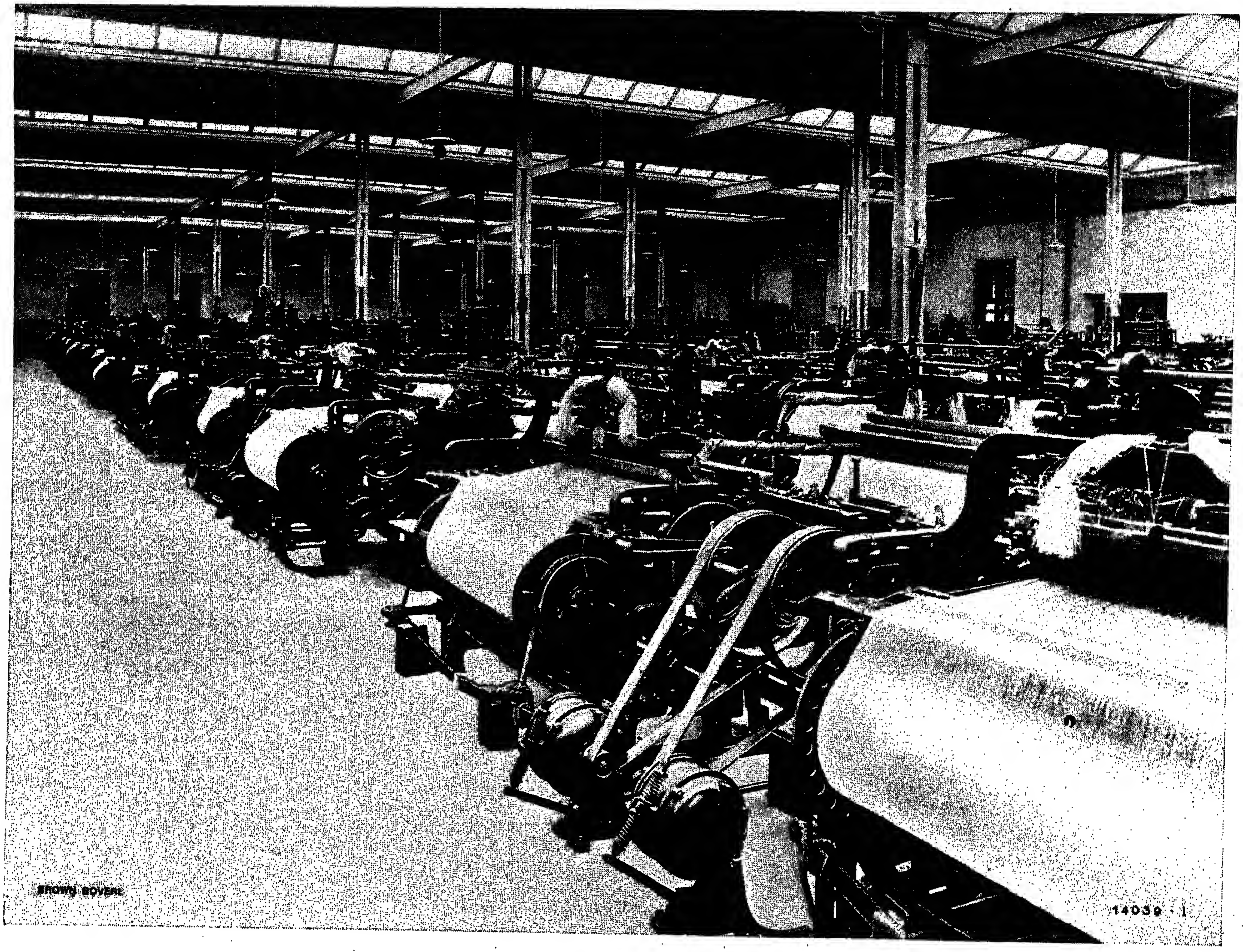
EDITED BY BROWN, BOVERI & CO., BADEN (SWITZERLAND)



TRAIN DRAWN BY BROWN BOVERI ELECTRIC LOCOMOTIVE LEAVING ZURICH MAIN STATION
on the recently electrified Zurich-Zug, section of the Swiss Federal Railways.

CONTENTS:

ELECTRIC DRIVES FOR INDUSTRIAL PLANTS



WEBER & Co., AARBURG (SWITZERLAND).
Individual drive of 200 weaving machines by Brown Boveri weaving-machine motors.

TEXTILE, PAPER-MAKING, AND PRINTING WORKS
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THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & CO., BADEN (SWITZERLAND)

VOL. X JULY, 1923 No. 7

The Brown Boveri Review is issued monthly. Single numbers: 1.20 francs (1 shilling). Yearly subscription: 12 francs (10 shillings).

THE BROWN BOVERI PHASE ADVANCER.

Decimal index 621. 313. 006 + 621. 313. 64.

SUMMARY. 1. The meaning of power factor. 2. Disadvantages of a low power factor in alternating-current systems. 3. Methods of improving the power factor. 4. The Brown Boveri phase advancer. a) Principle. b) Construction. c) Drive. d) Connections. e) Influence of the phase advancer on a motor. f) How to determine which motors should be compensated. 5. Comparison of the different methods of correcting the power factor in an alternating-current system.

1. THE MEANING OF POWER FACTOR.

If a consumer connected to a direct-current system is supplied with a certain amount of power at a given pressure, the strength of the current can be at once determined. In an alternating-current supply system, on the other hand, only the smallest attainable value of the current is found from the power and tension; this minimum current is called the watt-current. The actual value of the current I flowing is generally greater, and it is customary to speak of it as being composed of two parts: the watt-current I_w, and the wattless current I_{wl}. The relation between the three currents is given by the equation:

$$I^2 = I_w^2 + I_{wl}^2.$$

Like the total current, the wattless portion is an alternating one. It reaches its maximum value either a quarter of a period after or before the pressure has reached its highest value. In the first case, it is called lagging, and in the second, leading. At any moment, a leading current and a lagging current flowing in the same conductor have opposite directions, and the total wattless current is the difference of the two. The relation between the current I, the power P and the supply pressure E of a three-phase system is:

$$I = \frac{P}{\sqrt{3} \cdot E \cdot \cos\varphi}$$

The expression "$\cos\varphi$" in this equation is that which receives the name power factor; its value is

$$\cos\varphi = \frac{P}{\sqrt{3} \cdot E \cdot I} = \frac{I_w}{I}$$

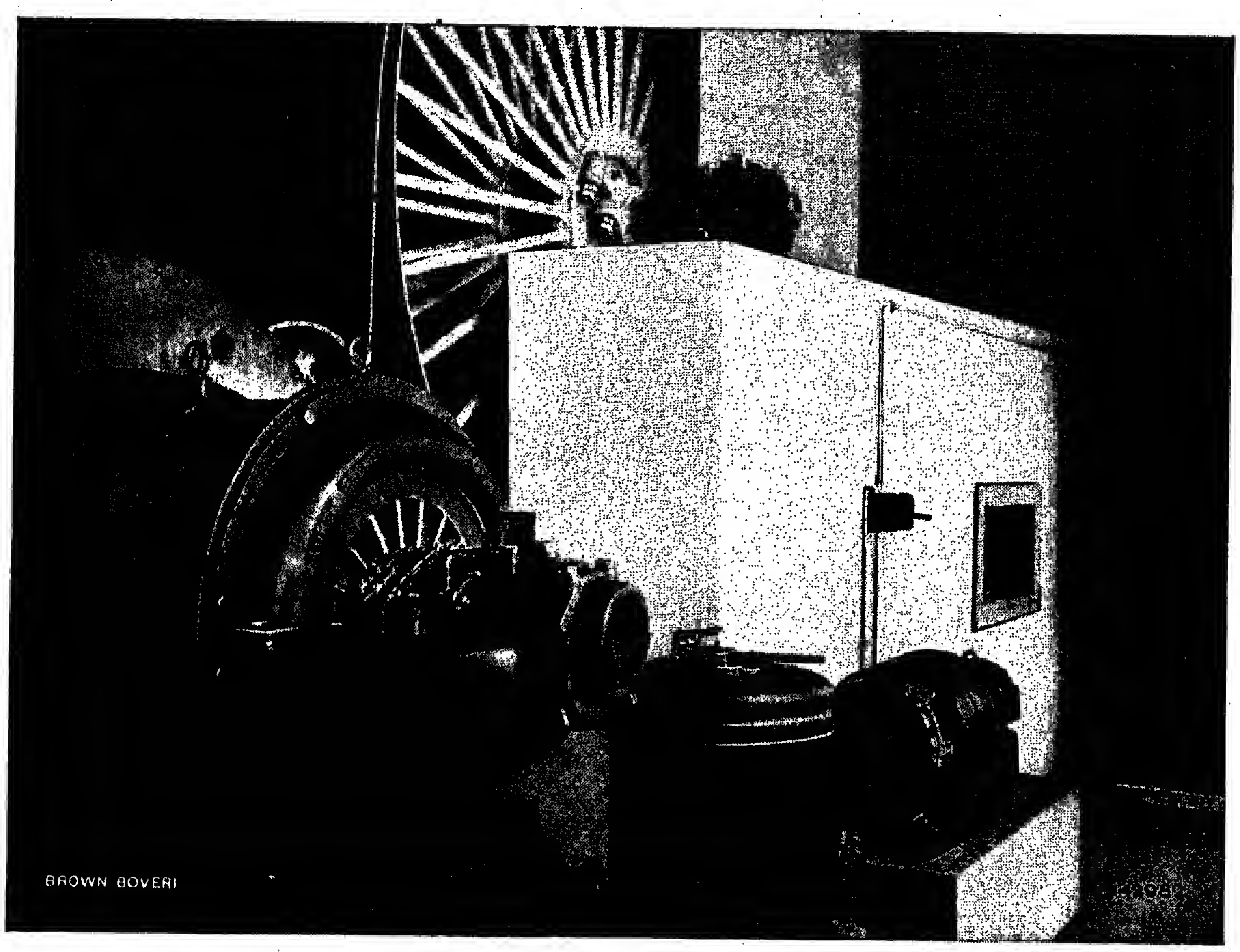


Fig. 1. — Three-phase induction motor, 185 kW, 600 r.p.m., 220 V, 50 cycles with a phase advancer for improving the power factor from 0·87 lagging to 0·98 leading, and relieving the system of 160 wattless kVA.

The product $\sqrt{3} \cdot I_{wl} \cdot E$ is often called the wattless power, and is measured in volt-amperes or kilovolt-amperes. The highest possible value of the power factor is unity. When this is attained, the wattless current is zero and only watt current flows in the conductor. In the majority of plants, the value of the power factor is considerably lower than unity, and varies usually from 0·6 to 0·85.

The fall in the value of the power factor is, for the most part, due to induction motors connected to the system. These machines draw a lagging wattless current (the magnetising current) from the mains for exciting their field. At no load, this current can be about 30 — 50 % of the normal full-load current, rising, however, only slightly as load is put on the motor. Since the watt current is roughly proportional to the load, it follows that the power factor rises with an increasing load — it

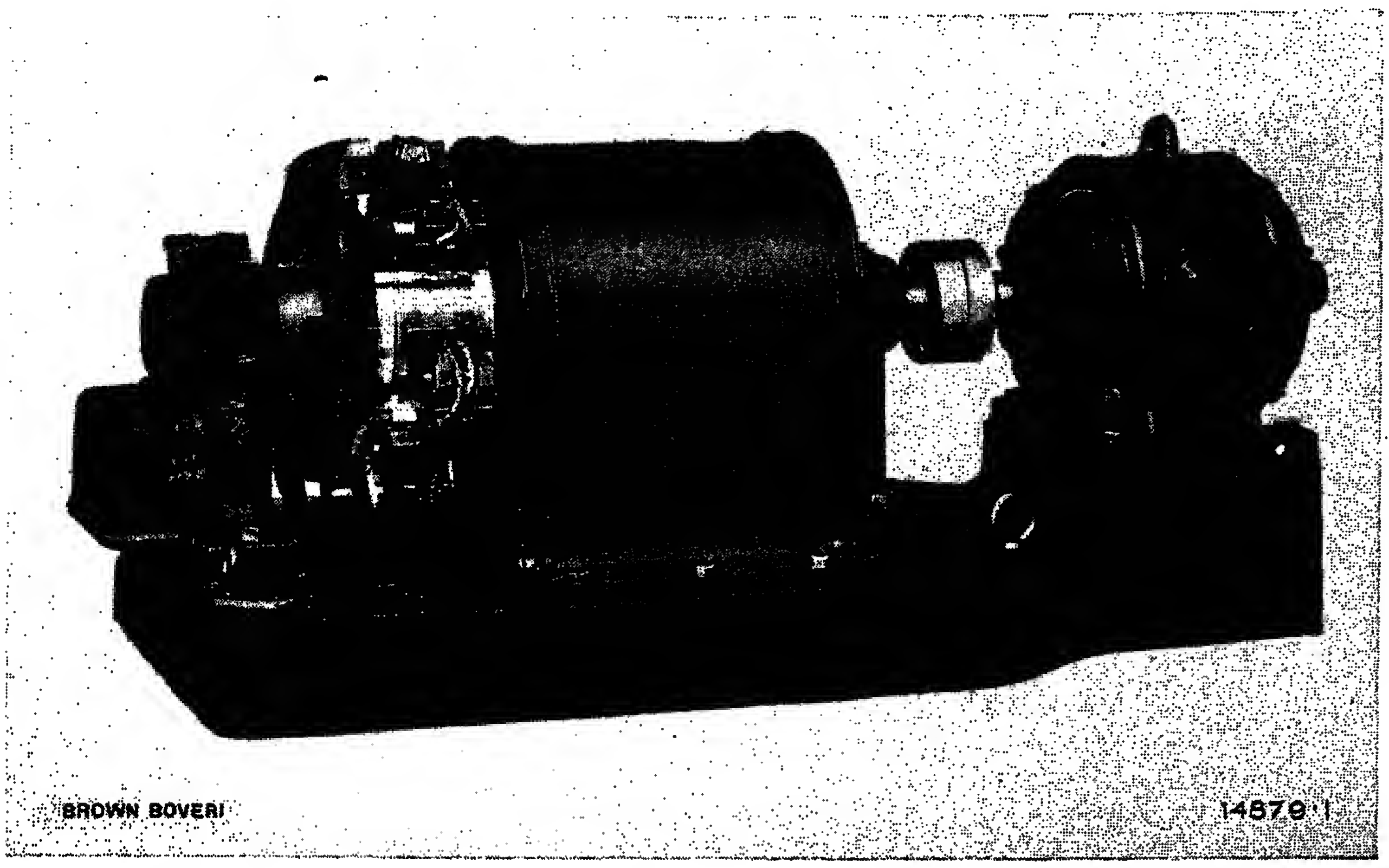


Fig. 2. — Brown Boveri phase advancer set (single type).

can, however, never reach unity. At no load, the power factor is very low, being only 0·10 to 0·15. The wattless current flowing in the mains is the sum of the wattless currents of the individual motors. The power factor of a plant is very unfavourably influenced by the use of slow-running motors, which take a large magnetising current, and by motors running on light load or no load.

2. DISADVANTAGES OF A LOW POWER FACTOR IN ALTERNATING-CURRENT SYSTEMS.

No power is transmitted by the wattless current, but it causes the same losses as a watt current. If the power factor has the value $\frac{a}{100}$, the total current is $\frac{100}{a}$ times, and the total heat losses $\left(\frac{100}{a}\right)^2$ times larger than would be the case if the same power were transmitted with unity power factor. The losses are increased in all portions of the installation, that is to say, in the generators, transformers and supply cables, and they can reach a considerable value, especially in the latter. Moreover, the kilowatt capacity of the generators and transformers is greatly reduced by the increased losses. The lagging wattless current also causes a large pressure drop in the whole system, which is greater than that due to a watt current of the same strength. On account of this, it is more difficult to keep the pressure constant, and for the same reason, the capacity of the plant may be reduced.

If an increased output is required from an installation which, with respect to losses or pressure drop, is already at the limit of its capacity, it is therefore possible to avoid the otherwise necessary extensions to the plant if the power factor is improved. Since additions to the generating plant are, in practically all cases, more expensive than the raising of the power factor according to one of the methods described later on, the latter is to be preferred. When a new generating plant is being designed, the capital cost can be kept down if it is planned on the basis of a higher power factor than that which would be reached without employing any special means for improving it.

Users of electrical energy who have their own generating plant can increase the power available and reduce the losses by power-factor compensation, while, at the same time, it is easier to keep the pressure constant. Although, on the other hand, consumers who take their energy from a supply company are not interested in the losses on the mains side of their meter, they must not overlook the losses in the cables leading from the latter to their machines, as such losses represent so much energy that must be paid for over and above the effective power used. The losses in question can be so high that the cost of current can be considerably reduced by correcting the power factor. The saving will naturally be still greater if the price per kilowatt-hour is made to depend on the power factor of the consumer's installation — a system of charging which is now being adopted more and more (see The Brown Boveri Review, 1922, No. 8).

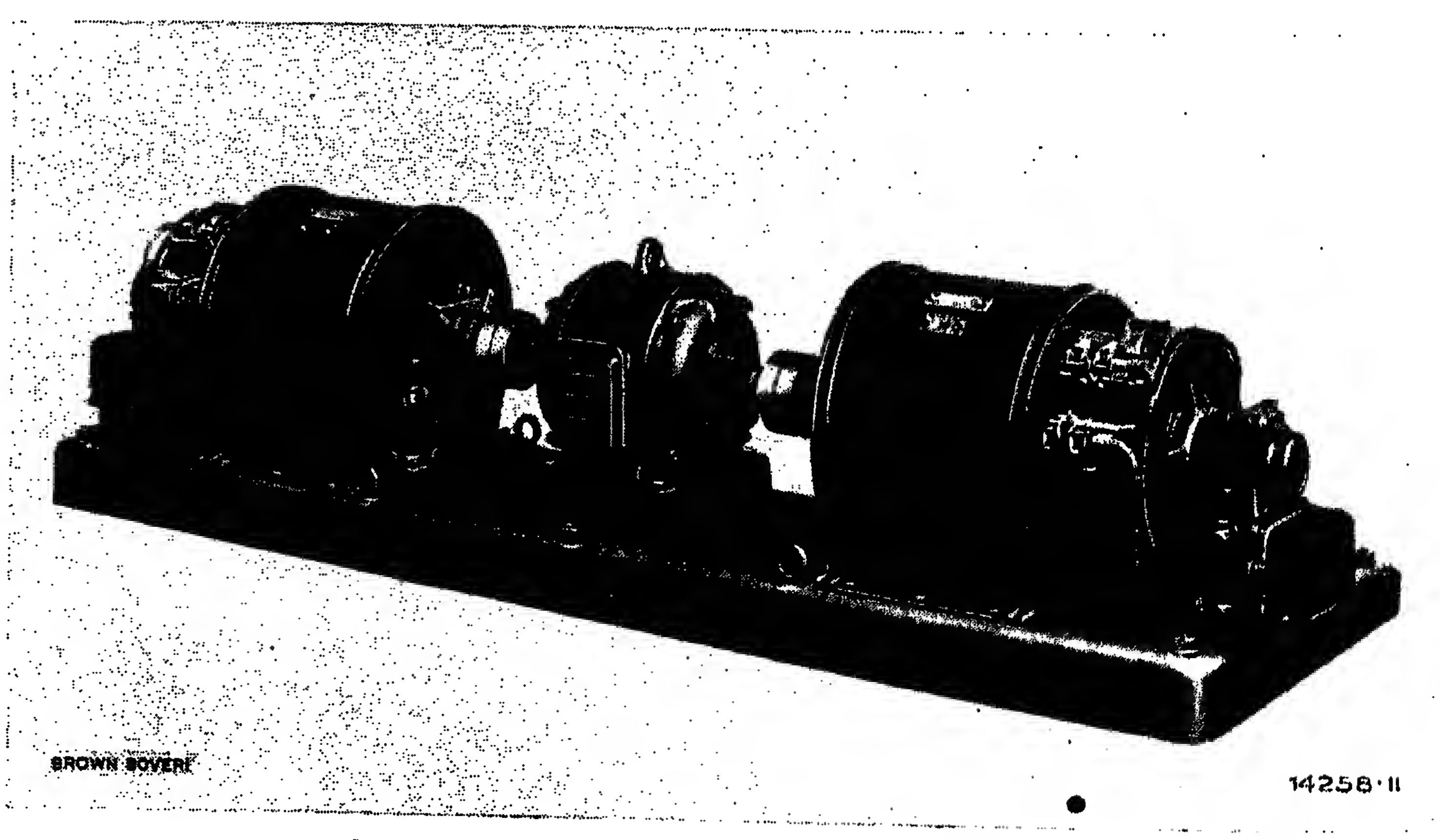


Fig. 3. — Brown Boveri phase advancer set (double type) for bringing the power factor of a three-phase induction motor, 550 kW, 200 r. p. m., 530 V, 50 cycles, from 0·8 up to unity, and saving 450 wattless kVA.

3. METHODS OF IMPROVING THE POWER FACTOR.

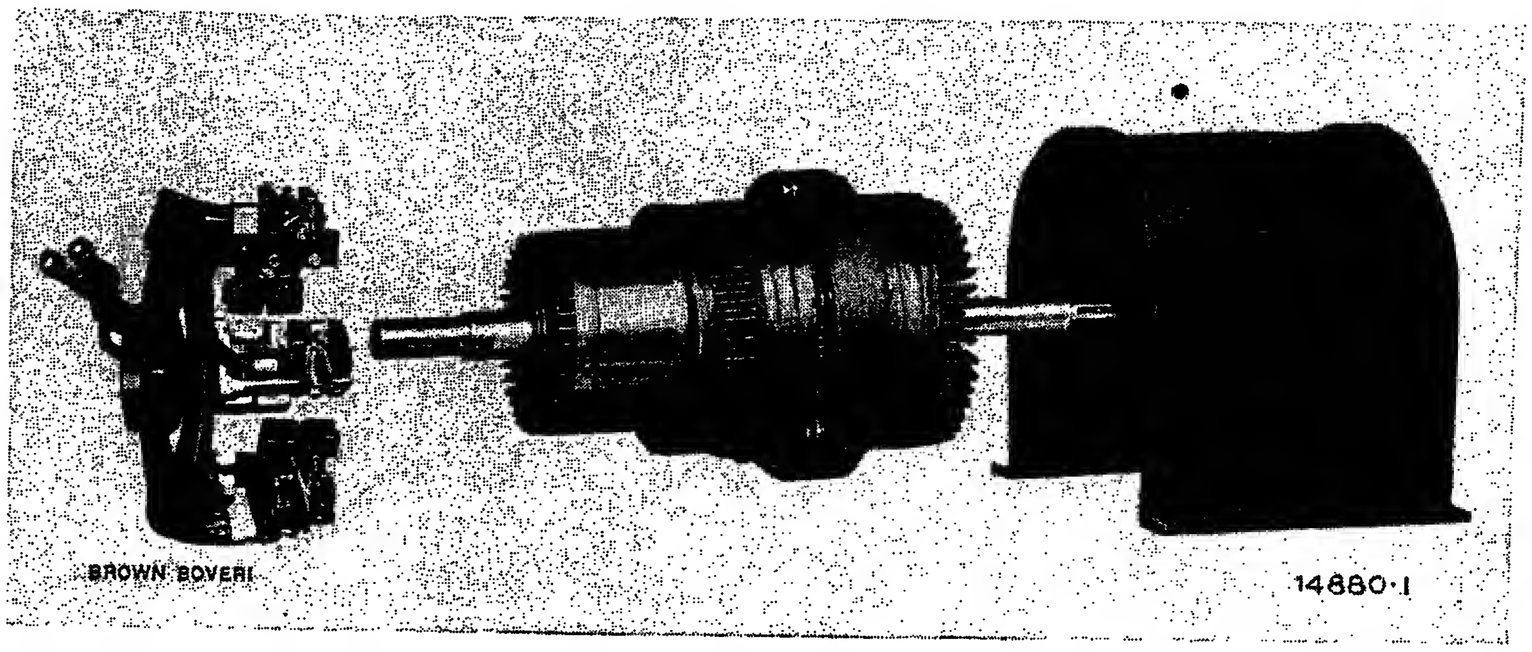


Fig. 4. — Brown Boveri phase advancer, dismantled.

As the poor power factor is caused in the majority of cases by the induction motors connected to the mains, the obvious solution is to raise the power factor of these machines, or to replace them by motors of a different type having a better inherent power factor. The improvement of the power factor of an induction motor is called phase compensation, and is attained by connecting a rotating phase displacer in the rotor circuit of the motor. By this means, it is possible to advance the power factor of the motor so far that it takes up leading current. It is for this purpose that the Brown Boveri phase advancer, of which a description is given hereafter, has been designed. The kinds of motor available with a good inherent power factor are the synchronous motor and the synchronous induction motor, both of which can work with unity power factor, or, if overexcited, with a leading power factor. Occasionally, the motor is not called upon to deliver any mechanical energy, but simply to run light and take up leading current, the value of this being so adjusted that it corresponds to the lagging current taken by the other motors connected to the system, so that in the latter only pure watt current flows. The synchronous motor operates here exactly like a condenser, which type of apparatus is occasionally used instead of this kind of motor. Finally, the power factor can by improved in a marked manner by choosing motors and transformers of a suitable size, and by avoiding long periods of light running. This branch of the subject will, however, not be further discussed here.

4. THE BROWN BOVERI PHASE ADVANCER.[1]

(a) Principle.

The power factor of an induction motor with a given magnetising current can be improved by transferring the latter partially or entirely from the stator to the rotor, so that the mains are correspondingly freed from the supply of this current. In order that the rotor current of an induction motor can have the necessary magnetising effect, it must be displaced so that it leads with respect to the current in the uncompensated motor. A pressure leading with regard to the current must therefore be introduced into the rotor circuit, and the duty of the phase advancer is to supply this pressure. This machine (Fig. 4) consists of a direct-current armature with a commutator having brushes placed 120 electrical degrees apart. Since the phase advancer must always be designed for a large current and a low pressure, its armature core is short and its commutator long. If the rotor current of the motor to be compensated, that is, a low-frequency polyphase current, is supplied to the commutator, the phase advancer when standing still will operate as a choke coil. Its effect, therefore, will be to give rise to a lagging pressure, whose magnitude depends on the frequency, i. e., on the speed with which the field produced by the polyphase current cuts the winding. The speed of rotation of this field in space depends on the periodicity of the exciting current, but not on whether the phase advancer is in motion or standing still, as any influence on the disposition of the current and of the field in the phase advancer (considered from a fixed point outside the latter) due to movement of this machine is nullified by the effect of the commutator and the stationary brushes. Consequently, if the winding rotates in the same direction as the field, the speed at which the two cut one another decreases, and the lagging pressure is reduced. The latter becomes zero when the speed of the winding is the same as that of the field. When, however, the phase advancer rotates quicker than the field, the relative movement between the latter and the winding will have the opposite sense, with the result that the induced pressure will be reversed in direction, and become leading, as required, so that the phase advancer operates like a condenser. As the speed of the field corresponds to the frequency of slip of the induction motor, which amounts to $^1/_2$—2 cycles per second, while a frequency of rotation of 30—50 cycles is usually chosen for the armature and commutator, the relative speed between the field and the

[1] Cf. A. Scherbius: "Eine neue Maschine zur Kompensation der Phasenverschiebung von Ein- und Mehrphasen-Induktionsmotoren." Elektrotechnische Zeitschrift, 1921, No. 42.

winding is high, and therefore a considerable leading pressure can be attained with quite a small phase advancer.

(b) Construction.

A noticeable feature about the design of the phase advancer is the absence of a stator. In order, however, to provide a closed path for the flux, the armature core is so designed that it extends radially well beyond the winding, which is in entirely closed slots. A stator can be dispensed with, since the machine is only required to give a leading pressure without having to supply any energy either in electrical or mechanical form. A light enclosing cover of sheet iron takes the place of a stator, and serves to protect the rotating parts and define the path of the cooling air. The simplicity of the design makes for great reliability, which is one of the leading features of the phase advancer.

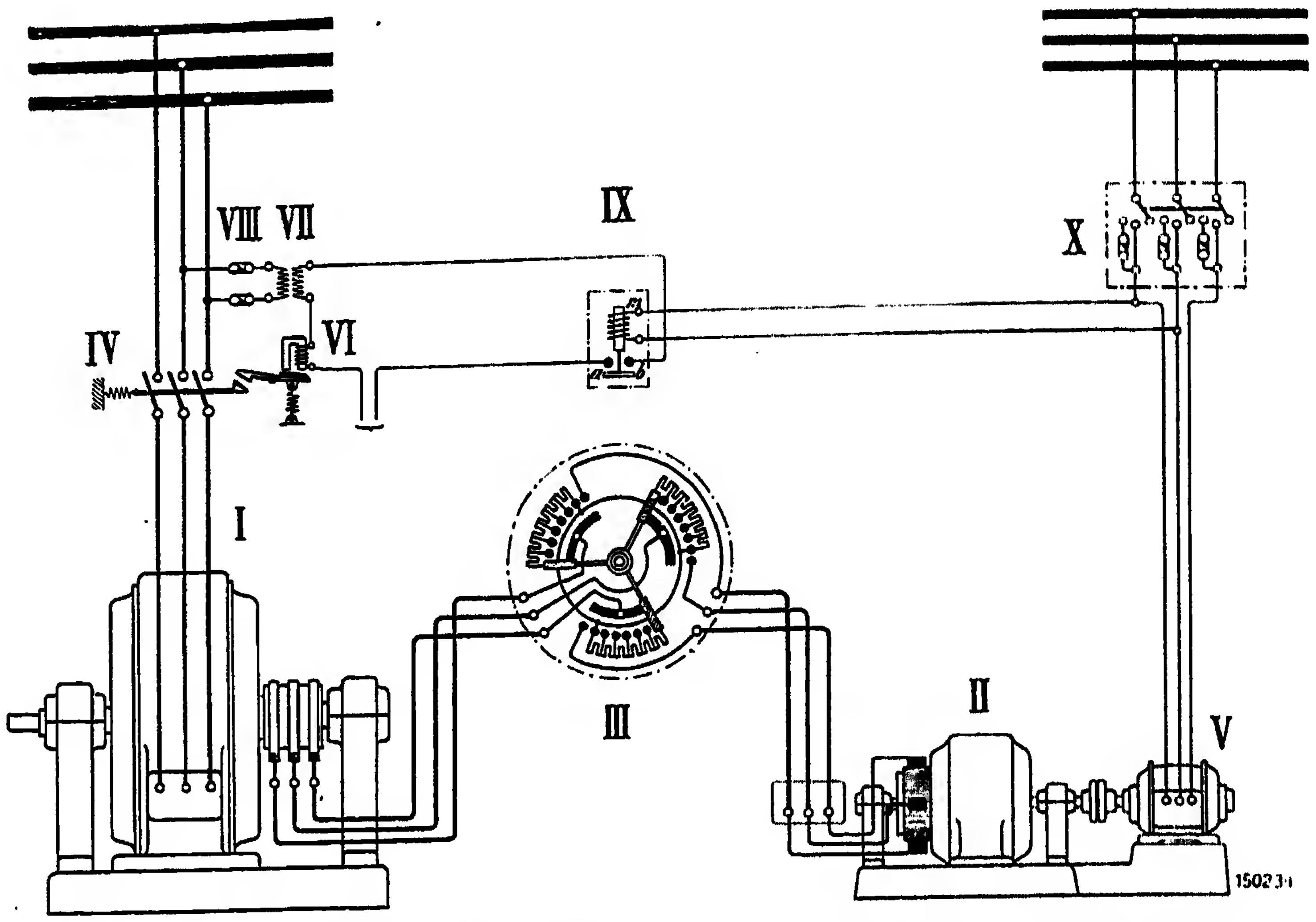


Fig. 5. — Diagram of connections of an induction motor with phase advancer.

I. Main motor.
II. Phase advancer.
III. Rotor starter with change-over device.
IV. Switch.
V. Auxiliary motor.
VI. No-volt release.
VII. Potential transformer.
VIII. Fuses for ditto.
IX. Contact relay.
X. Switchbox.

(c) Drive.

As the machine does not develop any torque, its armature must be rotated by outside means. For this purpose, the main motor itself can be utilised — in which case either direct coupling or a belt drive may be adopted — or a separate small auxiliary motor, which is generally of the squirrel-cage type. This latter kind of drive is as a rule preferable, since it permits of greater freedom as regards the place where the phase advancer can be situated. All chance of the drive of the latter failing must be eliminated by suitable attendance in the case of belt drive, and by some kind of electrical interlocking device, such as that described under *(d)*, with an auxiliary driving motor.

This latter machine has only to overcome the frictional losses of the phase advancer, which amount to about $^1/_3$ % of the output of the main motor. In order, however, to ensure sufficient starting torque, even with reduced pressure, it is usual to employ an auxiliary motor that has an output equal to $^1/_2$—$^3/_4$ % of that of the large motor.

(d) Connections.

A typical diagram of connections of a Brown Boveri phase advancer is shown in Fig. 5. Between the mains and the large motor is the usual switchgear, while the phase advancer is connected to three contacts on the rotor starter, so that the rotor of the main motor is switched over on to the phase advancer at the end of the starting operation. A separate change-over switch is used, however, when the rotor current is high or when the phase advancer is added to a motor which is already installed with its starter. In order to exclude the possibility of the main motor being started before the phase advancer is running, an electrical interlocking device is fitted. This also switches off the main motor should the current supply to the auxiliary motor be interrupted for any reason. Besides the arrangement shown in Fig. 5, there are various others which are used to suit particular requirements.

(e) Influence of the phase advancer on a motor.

Since the effect of the phase advancer is to cause part of the magnetising current of the main motor to be supplied by the rotor, it follows that less magnetising current is taken from the mains by the stator, with a consequent improvement in the power factor. If all the magnetising current flows in the rotor, then none comes into the stator, so that the motor works with unity power factor. Further, if the magnetising current in the rotor is raised above that necessary for exciting the field of the main motor, the latter balances the excess by drawing from the mains a current in the opposite direction, i. e., a leading current, which again causes the total stator current to be higher than with unity power factor. The current flowing in the rotor is lower when the motor is slightly compensated than when

no phase advancer at all is used, but rises when the compensating effect is increased.

As long as the main motor is not over compensated, that is to say, the power factor is not made to lead, the heating losses in the stator diminish, due to the reduced current flowing in that part of the motor, whereas, above a certain amount of compensation, the heating losses in the rotor increase, but always in a smaller proportion than the reduction of the stator losses, so that the total heating losses of the motor as a whole are reduced. When the losses in the phase advancer are taken into account, the net efficiency of the motor is found to remain unchanged or to fall only by a negligible amount (up to about 1%). If the power factor is made to lead considerably, the drop in efficiency would, of course, be somewhat greater.

The improvement of the power factor effected by a given phase advancer depends on the load of the main motor. At no load, the rotor current is zero, and the phase advancer causes no correction; on the other hand, even on light loads, quite appreciable improvement of the power factor is obtained. Generally it can be raised to about unity at any load from $^1/_3$, or in certain cases even from $^1/_4$, of the normal load right up to the overload capacity of the motor, thanks to a special design patented by Brown, Boveri & Co. Absolute no load scarcely occurs under actual running conditions, as a certain amount of current is necessary for overcoming frictional losses, etc.

It should be noted that at very light loads the power factor gives no definite measure of the amount of wattless current. Since the power factor represents the proportion between watt current and total current (see page 119), it is evident that its value depends just as much on the amount of watt current as of wattless current. Now, the watt current only varies within a comparatively limited range between full load and fractional loads, but when the motor runs light, its value depends on the losses alone, and these can vary considerably, which also influences the value of the power factor. When the motor is running on no load, the latter is, therefore, just as much a measure of the losses as of the wattless current. It would be more to the point in the case of no load or very light load to indicate, instead of the power factor, simply the amount of wattless current, or the wattless power, or the proportion the one or other of these bears to the value at full load.

In Fig. 6, the curves a and b show the power factor of a 300-kW motor as measured without and

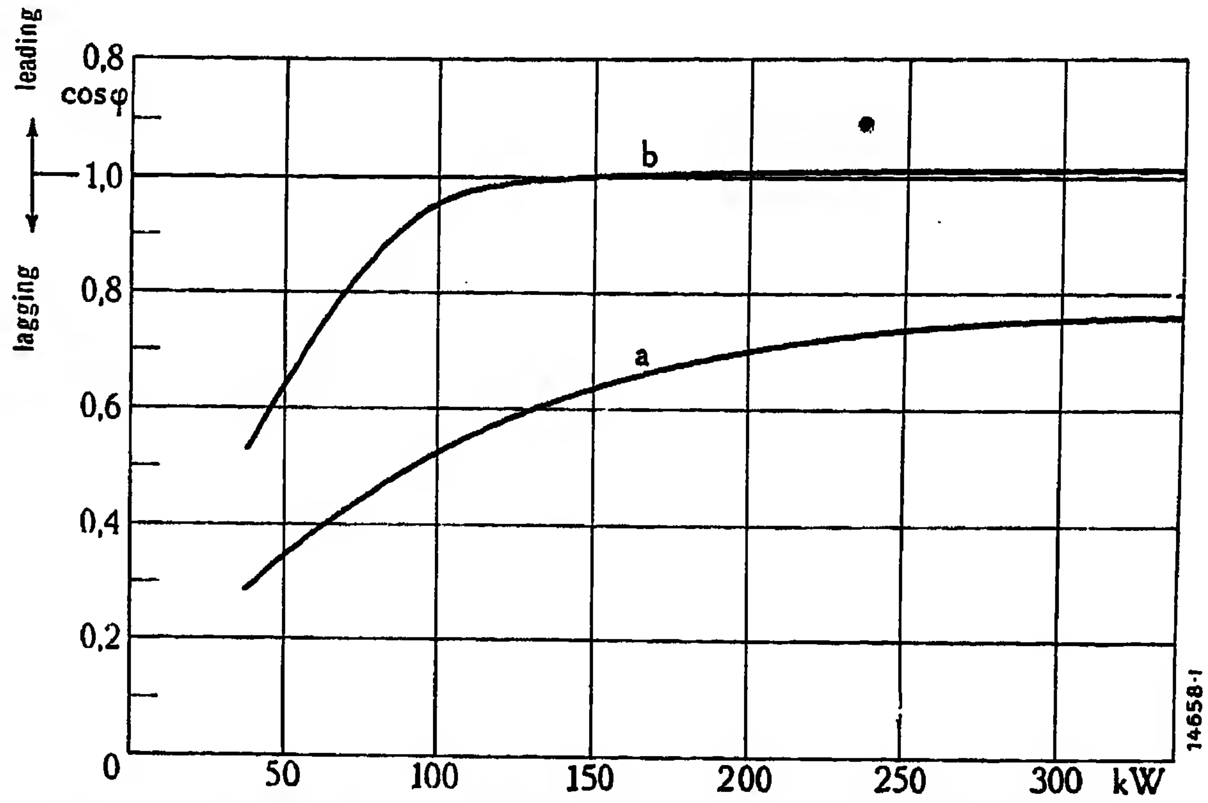


Fig. 6. — Power factor of an induction motor, 300 kW, 160 r. p. m., as a function of the output.

a. Without phase advancer. b. With phase advancer.

with a phase advancer respectively. The corresponding wattless power taken from the mains, which is proportional to the wattless current, is given by the curves a and b in Fig. 7. The difference between these latter curves is indicated by curve c; this represents the wattless power saved by using the phase advancer. In this case, the main motor is slightly over compensated at full load.

Since the slip of the induction motor is proportional to the losses in the rotor circuit, it will increase by about 25—75 % when the magnetising current flows in the rotor instead of in the stator. The speed of a motor will therefore fall about $^1/_4$—2 % when a phase advancer is employed. As seen above, however, the larger slip does not mean an increase in the total losses of the motor, as the stator losses are reduced at the same time.

The correction of the power factor possible with a given motor is limited in the first place by the maximum leading pressure allowable for the phase advancer, and secondly by the increase caused in the rotor current, since the losses must not exceed a certain amount on account of the permissible temperature rise. When the motor runs on partial loads, the rotor current is smaller, and so a much greater increase in it, and consequently in the amount of power-factor correction, is allowable than at full load. If full advantage is to be taken of this, the pressure of the phase advancer must be raised when the load on the main motor falls below normal. This is attained by running the phase advancer slowly at heavy loads and quickly at light ones, and in such cases, a shunt-wound direct-current motor best meets the requirements. Its speed has to be adjusted carefully, either by hand or automatically, so as to avoid overheating of the rotor winding which would take place

if the phase advancer ran quickly while the main motor was well loaded.

The use of a phase advancer not only raises the power factor, but also the breakdown torque of the induction motor, so that its momentary overload capacity is increased. This is a further important advantage of the phase advancer, especially with slow-running motors. Not infrequently, such machines must be of a larger size than necessary from the point of view of heating, in order to obtain the requisite overload capacity and a good power factor without a phase advancer; whereas, when the latter is employed, a smaller type of main motor can be chosen. Hence, it can happen that a better power factor is attained with a smaller total first cost. Even when overload capacity is of quite secondary importance, the possibility of raising the normal output of the motor by installing a phase advancer — due to the fact that the rotor losses do not increase as much as those in the stator decrease — should be borne in mind.

The fitting of a phase advancer in no way affects the asynchronous characteristic of the induction motor, and the drop of speed between no load and full load takes place in the usual way. There is, therefore, no question of hunting or falling out of step.

Even with a motor run as an induction generator, the phase advancer improves the power factor and overload capacity, but in this case, it is either necessary to reverse the direction of rotation of the auxiliary machine, as compared with that in which it runs when the main machine operates as a motor, or else to change over two of the connections between the phase advancer and the slip-rings.

(f) How to determine which motors should be compensated.

A motor that is to be provided with a phase advancer must have brushes for continuous contact. If the machine has brush-lifting gear, the necessary alteration — which may occasionally include more liberally dimensioned slip-rings — can generally be effected without any great expense. When the plant contains only one motor, it will, as a rule, be found advisable to correct its power factor only to about 0·95 to 0·98 lagging, since a greater improvement would mean increased losses in the main motor and a larger size phase advancer, while the further reduction in the stator current would be small. In such plants, it is sometimes not worth while using a phase advancer if the motor has normally a power factor of, say, 0·9 or more.

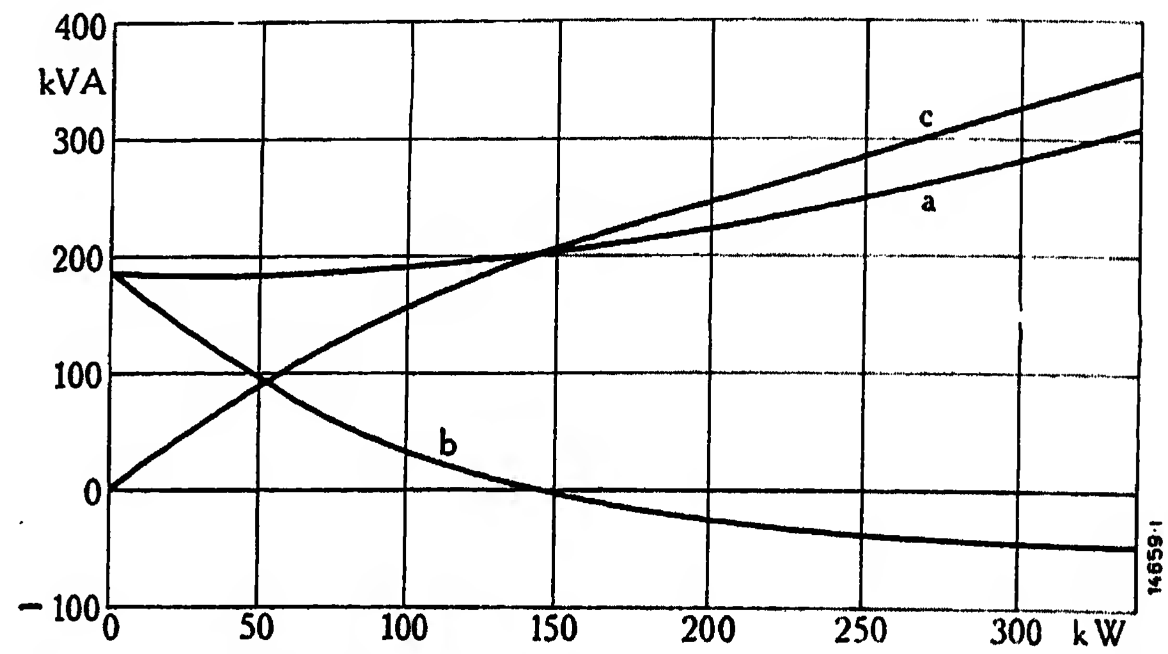


Fig. 7. — Wattless kVA taken by an induction motor, 300 kW, 160 r. p. m., as a function of the output.

a. Without phase advancer. b. With phase advancer.
c. Wattless energy of which the system is relieved with phase advancer.

The conditions are, however, quite different when numerous motors of various sizes are installed. In such cases, the overall power factor is usually rather poor, and if it is desired to improve the power factor of the plant by a certain amount, then a definite reduction of the aggregate wattless power taken by the motors must be aimed at. For this purpose, one or other of the motors can be compensated in a high degree, or else several motors compensated lightly. In individual cases, the question of which machine should be compensated may be settled by the fact that one of them is situated at a distance from the mains, the long cables causing relatively heavy losses when the power factor is low, or that one of the motors has insufficient overload capacity. If no machine has features which render it eminently suitable for having a phase advancer fitted to it, to obtain the desired reduction in wattless power, but all motors seem equally well adapted for this, the choice should be made on the basis of the following considerations: —

According to Fig. 7, the amount of wattless power in kVA of which the mains are relieved rises with increasing load on the motor compensated; consequently, a phase advancer should be fitted to those motors that work for the most part well loaded. Moreover, it is better to compensate the largest motors then a number of small ones, since a given

saving in wattless power drawn from the mains can be effected more cheaply by providing one large phase advancer for a large motor than several small phase advancers for small motors. The amount of wattless power saved bears the same relation to the output of the phase advancer (which has a definite value for each type) that the periodicity of the mains does to the periodicity of slip of the main motor. It follows, therefore, that the smaller the slip is, the greater is the amount of wattless power of which the mains can be relieved with a given size of phase advancer. Large high-speed motors have the smallest slip, and also a good normal power factor. The initial cost of the phase-advancer set necessary for saving a certain amount of wattless power in a plant will thus be smallest when just those motors are compensated that would scarcely require any improvement when considered by themselves. The same saving in wattless power can be effected by improving the power factor of a high-speed motor of 1000 kW with 1 % slip from 0·9 lagging to 0·975 leading, as by advancing the normal power factor of 0·7 of a slow-running motor of the same power with $2^1/_2$ % slip up to 0·95 lagging; in the latter case, the phase advancer has to give about 2—$2^1/_2$ times the output necessary with the high-speed motor. Further, as the power which the phase advancer must supply rises rapidly when the correction is carried to such an extent that the wattless power saved in kVA is more than about 75 % of the kW output of the main motor, it is not advisable to carry the compensation above this figure. Also from the point of view of running costs, the compensation should be kept within moderate limits, as the increase in the losses of the main motor and the phase advancer are small, or even zero, as long as there is not over-compensation, but rise rapidly if the power factor is advanced further.

Motors which, in conjunction with a slip resistance in the rotor circuit, utilise, at peak loads, the energy stored in rotating masses are frequently unsuitable for having a phase advancer of the above-mentioned statorless type fitted to them, as the possible compensation would then be small when much resistance is in the rotor circuit. Here the power factor can be corrected by employing a special regulating set like that used for the well-known Brown Boveri-Scherbius speed-regulating system, but usually of a simpler design, however. It can serve for merely improving the power factor or for causing at the same time the desired drop in the speed of the main motor with increasing load. Such an arrangement avoids the losses otherwise caused by the use of resistances for dissipating the slip energy. Moreover, it is possible to improve the power factor even at no load with such a set. For this reason, it may even enter into consideration instead of an ordinary phase advancer for compensating a motor which is used for a drive requiring no speed regulation.

The kind of drive for which the induction motor is used is not of any consequence, if only attention is paid to the points mentioned above. The phase advancer operates just as advantageously with constant load on the main motor as with heavy fluctuating loads. When peaks do occur, the increase in the overload capacity due to the phase advancer shows to its full advantage.

Compensation of the power factor of induction generators can also be of great importance in certain circumstances. Such machines supply watt current to the system, but as they draw from it at the same time wattless current which has to be furnished by alternators working in parallel with them, the current of the alternators is scarcely reduced at all — in some cases, it may be even increased when the induction generators are working. If, however, the latter are fitted with phase advancers, the alternators are relieved of supplying the wattless current, and it is only then that the benefit accruing from the employment of the induction generators to help the alternators is fully felt. In passing, it should be mentioned that even a compensated induction generator only operates satisfactorily when working on a system which is fed by an alternator at the same time.

5. COMPARISON OF THE DIFFERENT METHODS OF CORRECTING THE POWER FACTOR IN AN ALTERNATING-CURRENT SYSTEM.

The power factor may be adjusted either for the purpose of regulating the pressure, for reducing the heating losses, or for both these reasons together.

Since a lagging power factor results in a large pressure drop, and a leading power factor causes a rise of pressure in the mains, it is possible to adjust the pressure in a long supply line by taking

from it either a lagging or a leading wattless current at certain points. A phase advancer does not come into consideration for this duty, and recourse is had to a synchronous motor whose exciting current is mostly varied by an automatic regulator in such a way that the pressure in the line is kept constant.

When it is not a question of influencing the line pressure at one place so that it remains steady, but of having as far as possible only motors connected to the system which cause roughly the same pressure drop at light load as they do at full load, — special provision for keeping the pressure constant not being so necessary in this case, — then the induction motor with a phase advancer is very suitable. This is due to that feature of the phase advancer which, from another point of view, is considered undesirable, i. e., that it raises the power factor when the motor is loaded but not when it is running light. As the lagging wattless current falls (Fig. 7) when load is put on a motor provided with a phase advancer, it follows that the pressure drop of the wattless current is reduced, while that of the watt current, of course, increases. The one effect balances the other to a large extent, and the variation of the pressure drop in the line is smaller than with a synchronous motor or a synchronous induction motor. The lagging wattless current of these two kinds of machine increases when load is put on, assuming that the excitation is not adjusted in the meantime, and so there is a larger pressure drop in the mains, which is augmented by the watt current rising simultaneously. The same holds good for a reduction in the leading wattless current as for an increase in the lagging current.

It should be noted that if condensers are connected to the mains at various places they will not influence in the slightest degree the increase in the pressure drop caused by load being put on the motor.

This change in the drop is of considerable importance as regards the overload the motor can carry. Since the overload capacity is approximately proportional to the square of the terminal pressure, a large fall in the latter will bring down the overload capacity to a great degree. The pressure tends to fall as soon as an overload comes on, and therefore the question of overload capacity is to a large extent one of avoiding an excessive drop in the pressure. The phase advancer influences the overload capacity favourably, and in a twofold manner: by reducing the extent of the drop in pressure when the load comes on, and by actually increasing the overload capacity of the motor with constant supply pressure — as already seen in section 4 e.

If the power factor is to be improved for the purpose of minimising the heating losses, then the phase advancer can be employed, as well as the other methods indicated in section 3. Like the condenser, it has the advantage of only increasing the losses in the plant by a negligible amount. Apart from the large floor space taken up by the condenser, and the fact that it can have an undesirable effect on the system under certain circumstances, the question of initial cost and depreciation plays the main part in settling the question of which kind of apparatus should be installed for correcting the power factor. So far, condensers have not been employed in Europe to any extent.

When comparing the phase advancer with the synchronous motor, it is necessary to make a distinction between the case where the latter runs merely for the purpose of raising the power factor, and where it is required to give a mechanical output at the same time. With the latter, the decision is more difficult. While the capital cost is here also an important factor, figures with regard to this must be treated with caution, as they depend too much on the assumptions made, and can scarcely give a fair idea of things. It is necessary to consider the cost of each complete set, that is, of the induction motor with phase advancer on the one hand, and of the synchronous motor on the other. The losses of each must also be taken into account when making the comparison. Although these do not differ materially when the machines are loaded, the losses when running light are much greater, at least with the synchronous induction motor, than with an induction motor with phase advancer, provided that the excitation of the synchronous machine is not made to vary according to the load. This latter type of motor then takes a considerable amount of leading wattless power from the line, whereas the phase advancer is ineffective when the main motor runs light. The increased losses with the synchronous induction motor are justified when

it is desirable to take up leading current at no load, but they cannot be considered other than a disadvantage when no store is set upon this feature.

The adoption of a synchronous induction motor or an ordinary synchronous one with mechanical output cannot be considered in many places, e. g., where its characteristic features do not suit the drive in question. When heavy peak loads may occur, a motor with a synchronous characteristic is seldom desirable, and in such cases an induction motor with phase advancer is the appropriate solution, as such a machine still retains its asynchronous character, and is not only as suitable as an ordinary induction motor alone, but frequently still better, on account of its increased overload capacity.

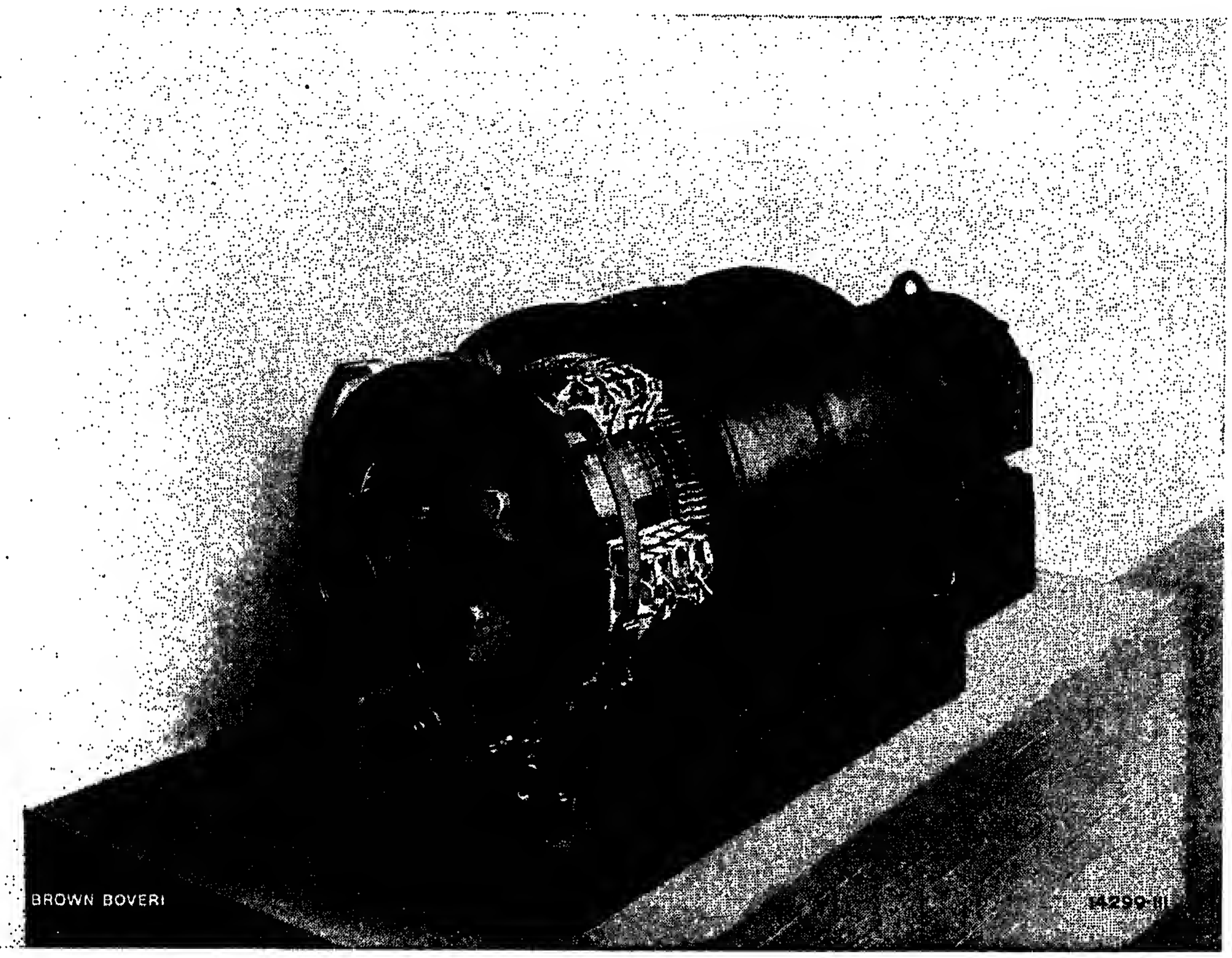


Fig. 8. — Brown Boveri phase advancer with its driving motor.

The only other practical alternative to a phase advancer is here a synchronous motor running light, and adjusted to take a leading current. As the comparison then lies between this machine and the phase advancer exclusive of the main motor, the balance as regards cost is in favour of the phase advancer. The light-running synchronous motor needs a watt input equal to at least 5 % of the amount of wattless power it saves, whereas the increase in the losses of the plant due to installing a phase advancer is only about 0—2½ % of the wattless power saved, corresponding to 0—1 % of the main motor output as mentioned above. The running costs of the phase advancer are therefore much smaller than those of a synchronous condenser. The initial cost of installing the latter type of plant will, of course, be kept down wherever possible by connecting only a few such machines of large capacity to suitable points of the supply system, instead of providing one for each induction motor that should have its power factor corrected. It is then, however, only possible to influence the losses in the mains between such points and the power station. With phase advancers, on the other hand, the losses in the connecting cables right up to the motor are reduced. Further, the advantage of better overload capacity, and, in certain circumstances, of the increased power the induction motor can furnish continuously must here also be put to the favour of the phase advancer, as the light-running synchronous motor has no effect of this kind on the induction motors in its neighbourhood.

When the operating conditions of a plant without any special devices for improving the power factor are looked into, it will be found, as a rule, that a considerable saving could be effected by power-factor correction. In many cases, this would be due to a reduction of the losses; in others, where the price per kilowatt-hour depends on the power factor, there would be the additional advantage of obtaining current on better terms; while in still other cases, extensions to the plant, which would otherwise be essential, can be postponed for years. Generally, it will be found that the best way to improve the power factor is to connect the phase advancers to individual induction motors. Besides the saving in the cost of current consumed, which can be stated directly in figures, there are advantages that cannot be expressed in this way: such as, smaller variation in the terminal pressure, higher overload capacity and even increased power of the motor. The results obtained with the phase advancer in numerous installations over a long period of years have proved that it is a most reliable machine, and the recognition of the advantages accruing from its use are leading to its more widespread adoption.

Dr. W. Seiz. (J. F. L.)

THE NEW TRANSFORMER TESTING INSTALLATION IN THE BADEN WORKS OF BROWN, BOVERI & CO. [1]

Decimal index 621. 795: 621. 314. 3.

IV. TESTING BAY FOR STANDARD MEASUREMENTS WITH SPECIAL INSTRUMENT TABLES.

The development in transformer construction has resulted in increasing severity of the conditions to be fulfilled by the materials employed, and the transformer designer is limited, particularly as to the magnitude of the pressure that can be dealt with, by the dielectric strength of the insulating material at his disposal. Nevertheless, no transformer that is not perfectly able to stand the exacting demands met with in practice can leave the Brown Boveri works, as each one has first to pass a number of searching tests.

The following measurements and tests ensure the timely discovery of any defects:—

1. The measurement of the transformation ratio— for checking the number of windings.

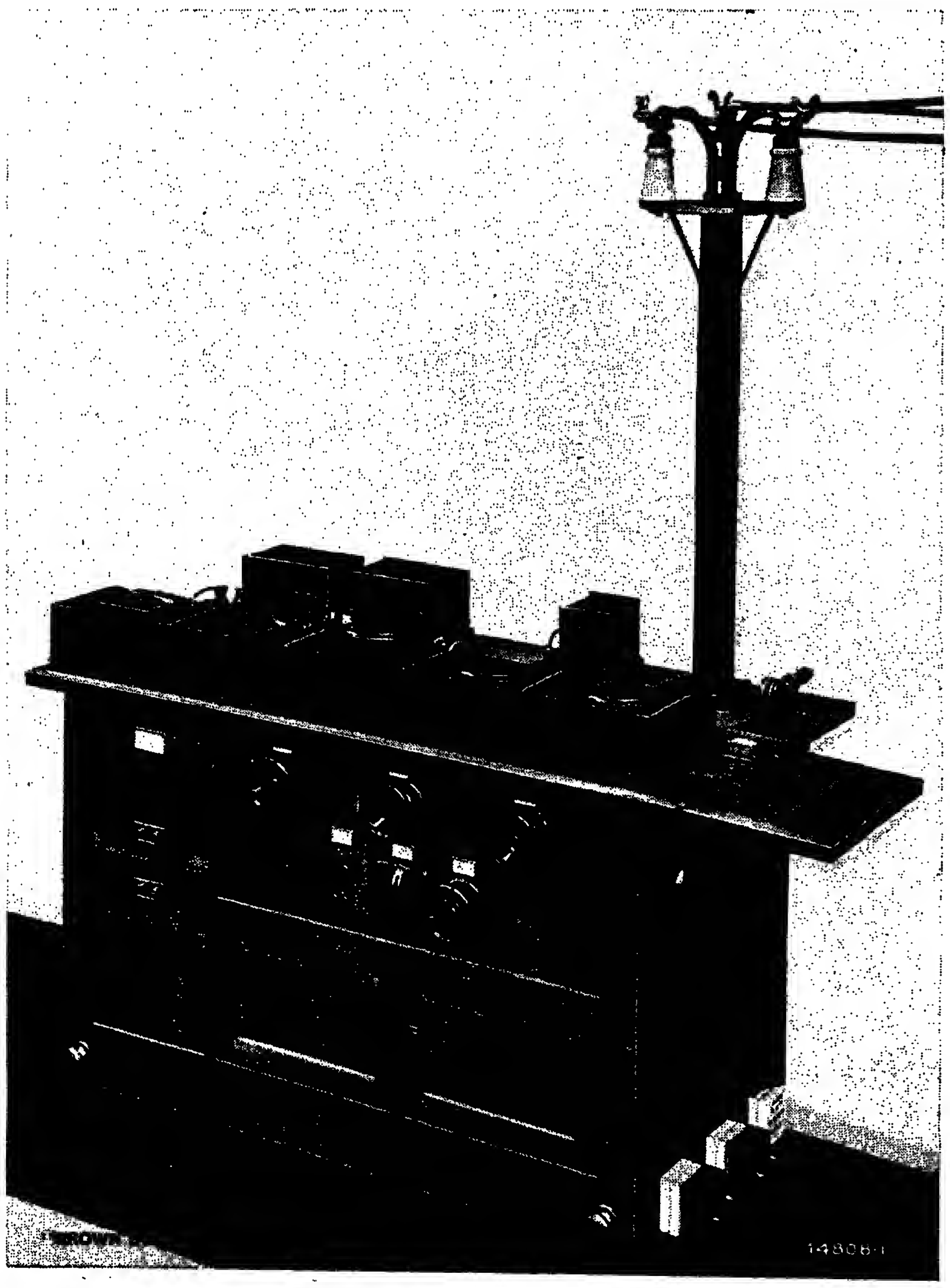


Fig. 7. — Instrument table for 400 A, 12'000 V.

2. The determination of the polarity—for checking the connections.

3. The measurement of the no-load losses— which is necessary for the determination of the efficiency.

4. The measurement of the copper losses with the transformer short-circuited—for checking the distribution of current in the primary and secondary windings. The extent of these losses must also be known for the determination of the efficiency and the pressure drop.

5. The measurement of the ohmic resistances.

6. The testing of the insulation resistance between the windings and the iron.

7. The testing of the insulation resistance between the windings themselves. For this purpose, the transformer is subjected to an increased pressure at a correspondingly high frequency.

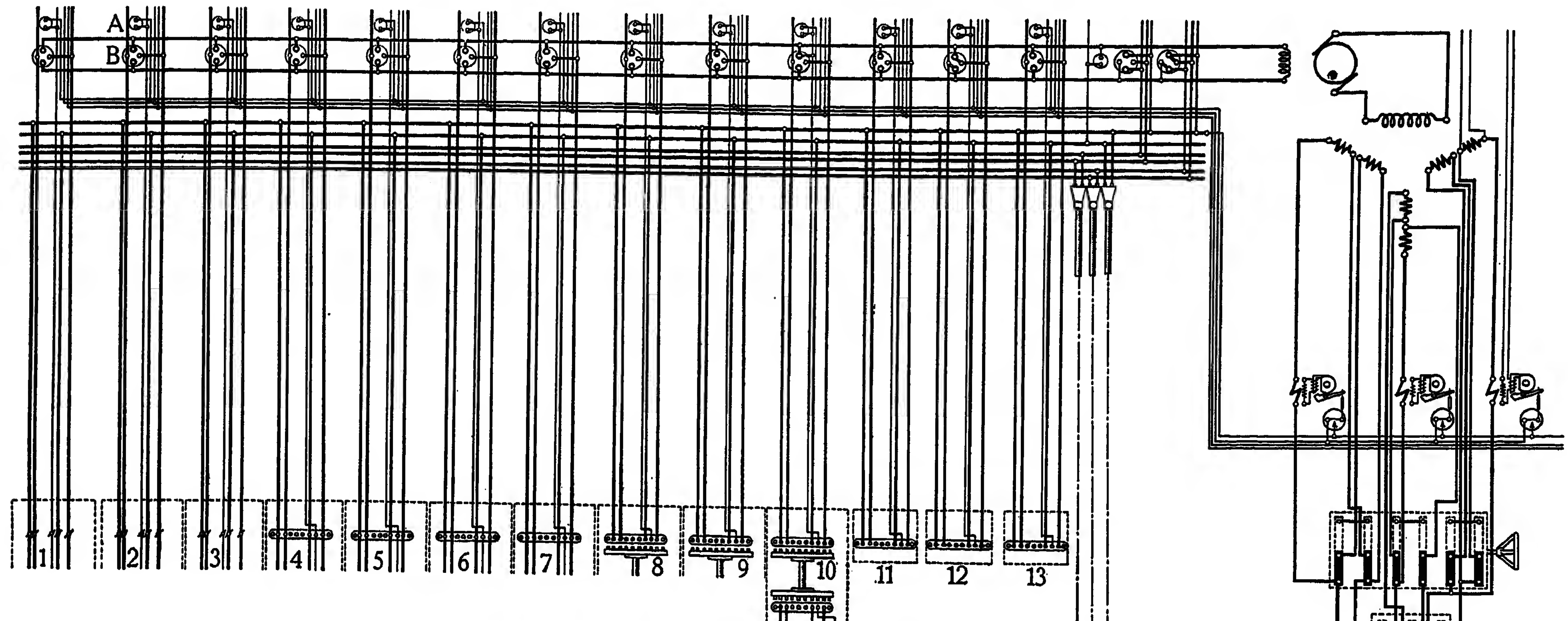
8. The surge test, which was introduced two years ago and serves to test the strength of the insulation, particularly that of the end coils next to the terminals, with a pressure many times greater than normal.

For making the above tests, which must be undergone by all power transformers, the testing bay is divided into two sections which adjoin one another. In one of these, the large transformers, i. e., those having outputs of about 1000 kVA and upwards, are tested and, in the other, chiefly the smaller transformers, with outputs from 1 to about 1000 kVA.

Fig. 1 is the plan of the whole testing department, including the dark room and the room for surge tests, both of which are described more fully later.

From Figs. 1 and 3 it is seen that the erection shop and testing section for small transformers are adjoining, while the heavy transformers are tested in the section next to the large erection shop.

[1] Concluded from June, 1923.



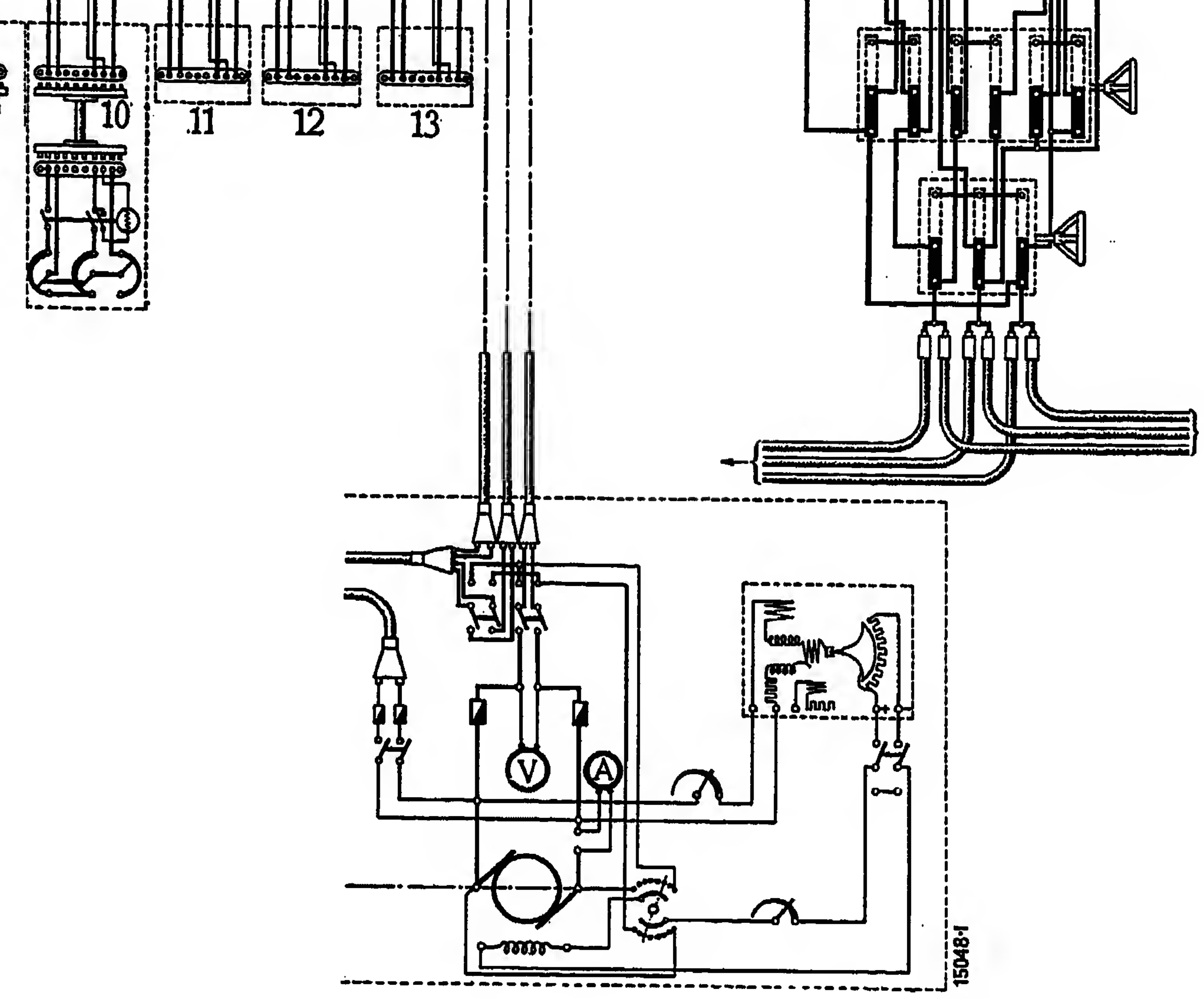


Fig. 8. — Diagram showing in principle the connections of the excitation selector panel, for one alternator and one instrument table only.

1—3. Leads from the selector boards in the machine room.
4—13. Junction points for instrument tables.
A. Sockets for plugs completing overload-release circuit.
B. Sockets for plugs completing field-rheostat circuit.

Before passing from the description of the distribution installation to the details of the actual testing plant, it should be mentioned that, for safety, all mains leading to the alternators and transformers are laid in channels, whether they are in the form of cables or bars — the latter being used for high tensions (3000—20′000 V).

The conductors pass from the selector boards to the junction points (Fig. 6), to which the specially constructed instrument tables are connected, short cables passing from the latter to the apparatus etc. under test. These tables are of two kinds, for pressures up to 3000 V and 12′000 V respectively. That shown in Fig. 7 is of the latter type, and constructed to take currents up to 400 A. The tables were designed with particular regard to the following points:—

1. As the rated pressure cannot usually be directly applied to transformers under test, it must be practicable to regulate the pressure of any of the alternators from each of the instrument tables, no matter to which of the junction points they may be connected.

2. The three-phase induction regulator in the machine room, which is used to supply current for making measurements, must also be controlable from the instrument tables.

3. It must be possible to include the current and pressure coils of the wattmeter, for making no-load and short-circuit measurements, directly in the measuring circuit, i. e., without the intermediate connection of current or potential transformers.

4. For checking the current on no-load and short-circuit tests, the use of a change-over switch should enable the current in the separate phases to be measured by a single ammeter, the pressure remaining constant.

5. From the instrument tables it must be possible to release, when necessary, the switches in the machine room that break the circuit of the 12′000-V cable from the machine-testing department.

To satisfy these conditions it was found necessary to fit a special excitation selector panel (Fig. 9) which enables the field of each alternator to be adjusted from any instrument table connected to any one of the ten junction points.

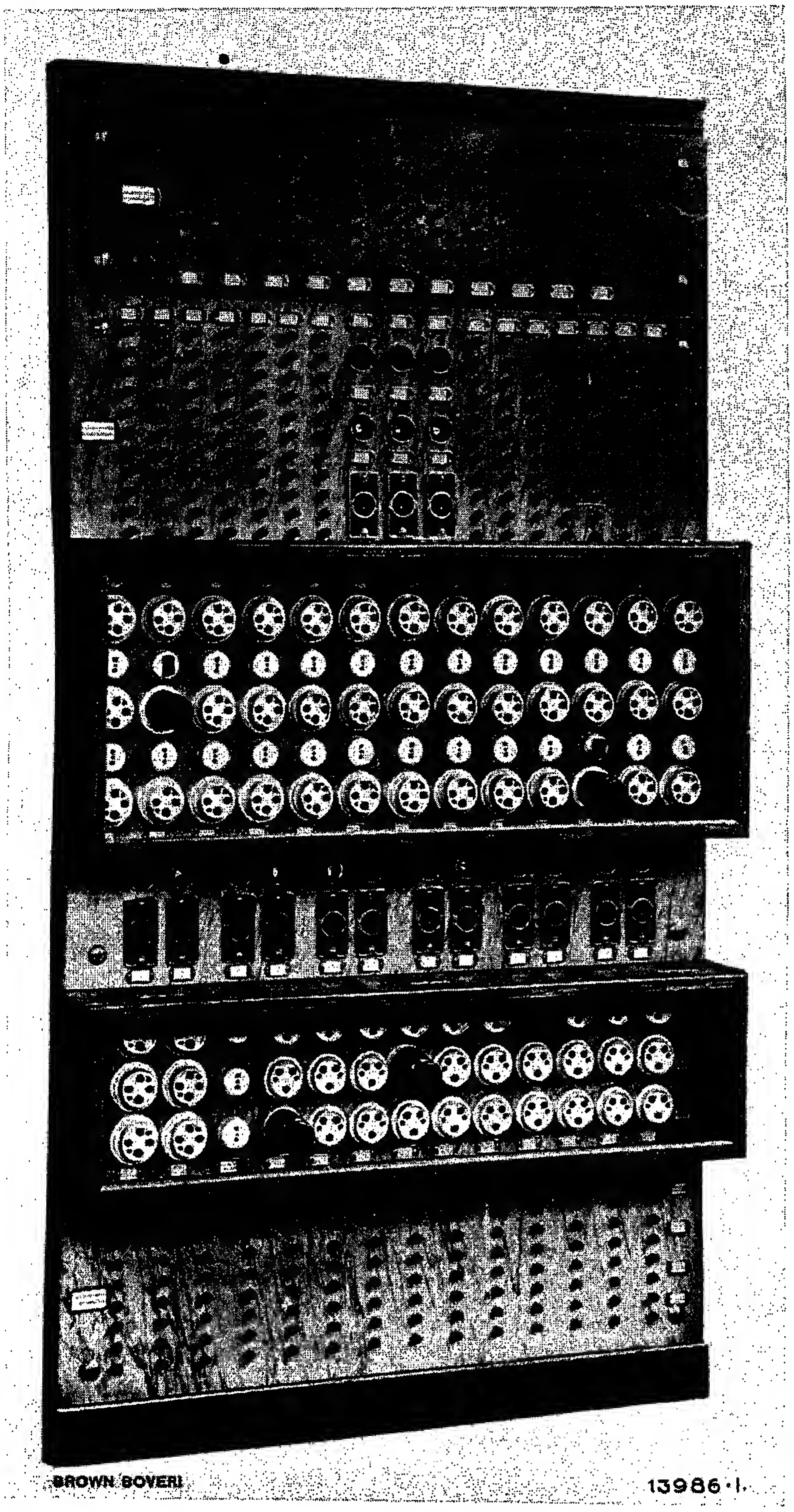


Fig. 9. — Excitation selector panel.

The range of connections provided by this selector is shown, for one alternator only, in Fig. 8. A direct-current generator, the pressure of which is kept constant by a quick-acting regulator, supplies the excitation selector panel. Each alternator has its own exciting machine the field of which is fed through the selector panel from the main exciter and controlled by the field rheostat on one of the instrument tables. To complete this rheostat circuit and that by which the automatic breaking of the field circuit is effected on overload, plugs are inserted in the rows of sockets (B) and (A) respectively. The sockets chosen correspond to the junction point occupied by the instrument table — for instance in Fig. 8, those corresponding to junction point 10.

The excitation selector panel not only deals with the alternator field current, but is also provided with push buttons for starting and stopping the driving motors of the alternators. These motors are all provided with automatic starters, the position of which is indicated by signal lamps mounted beside the push buttons. Similar buttons with signal lamps are also fitted for controlling the switches of the incoming 12′000-V three-phase cable. The panel is situated in the testing bay itself, and from the foregoing description it will be evident that, in addition to providing a means of controlling the alternator excitation, it is useful as an indication of the working conditions in the machine room.

Before closing this part of the description, mention must be made of the installation for the delivery and measurement of the constant flow of water that is particularly necessary for heating tests on large water-cooled transformers.

The 3000-litre cistern, seen in Fig. 3, is fed from the town water supply, and a four-inch distribution pipe carries the water to three junctions in the portion of the testing bay in which heavy transformers are dealt with. The water used during a test passes through a meter and, if desired, into a calibrated tank

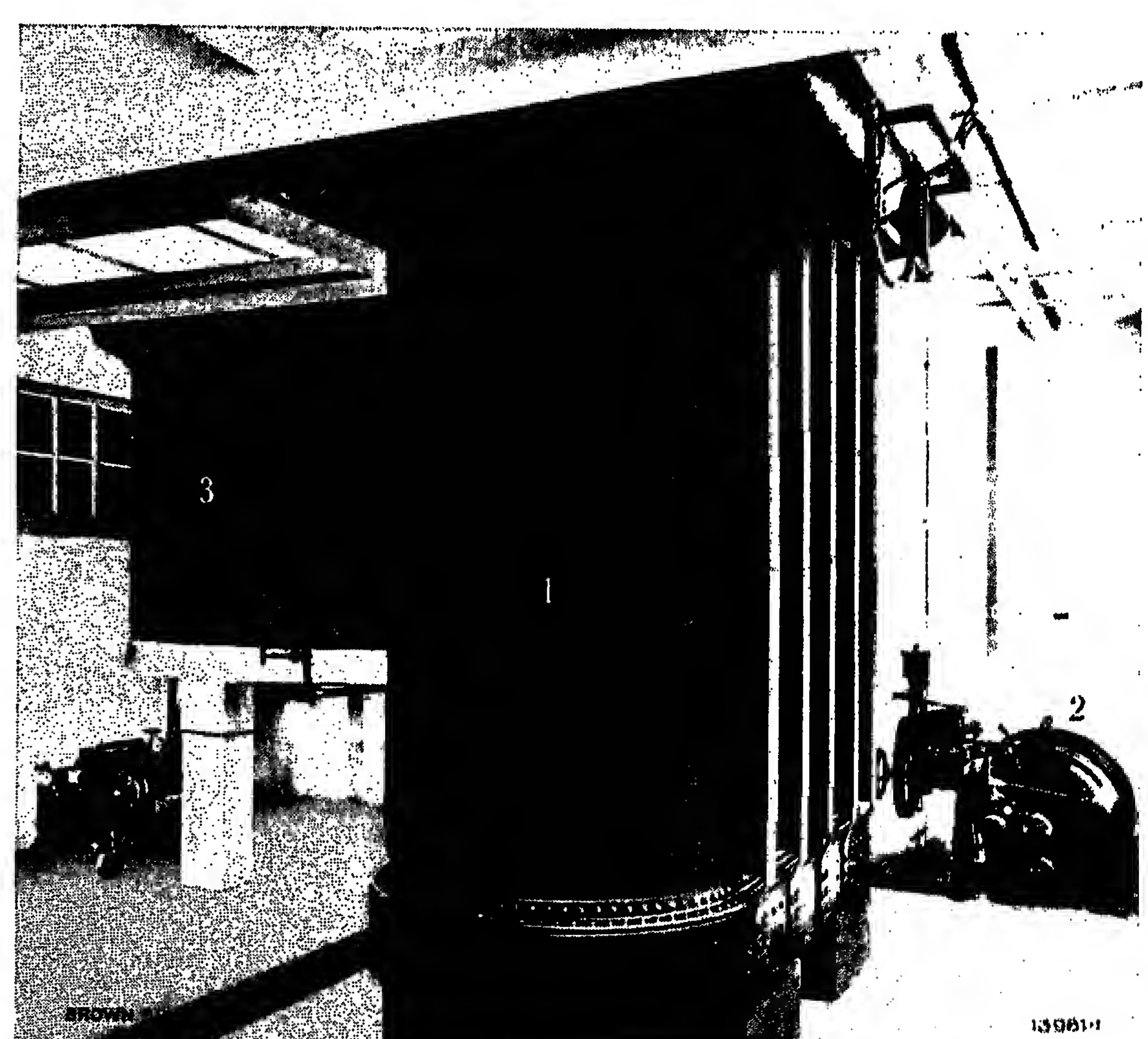


Fig. 10. — Part of the cellar bellow the dark room.
1. Testing transformer for 500 kV. 2. Induction regulator for same.
3. Oil tank.

of 200 litres capacity. This can be connected in series with the meter, so that accurate checking of the quantity of cooling water is possible under all circumstances.

V. DARK ROOM.

The thorough testing of all materials employed in the construction of machines and apparatus generally, prior to their manufacture, is carried to a specially high degree in the case of transformers, tests on insulating materials being the most important. All these detail tests naturally do not replace the thorough testing of the finished apparatus, so that a modern dark room was included in the plans for the new transformer testing department. It was designed and equipped to allow of the following tests being made:—

1. Tests on the dielectric strength of all the materials employed in transformer construction.
2. Insulation tests on finished transformers up to the largest units.

The plan of the dark room as well as its situation is shown in Figs. 1 and 3; its floor space measures 7·5 m × 9 m. A track is laid through the centre of the room, upon which trucks can be run for the transport of large apparatus.

Figs. 13 and 15 convey an idea of the care given to maintaining an absolutely level floor—a precaution of the greatest importance for the observers carrying out insulation tests in the dark.

Besides a carefully constructed testing plant for pressures up to 500'000 V, a cylindrical oil tank of 10 m³ capacity is installed in the dark room. For the testing of transformers, switches, and large insulators for outdoor use, artificial rain is provided by a system of sprinklers.

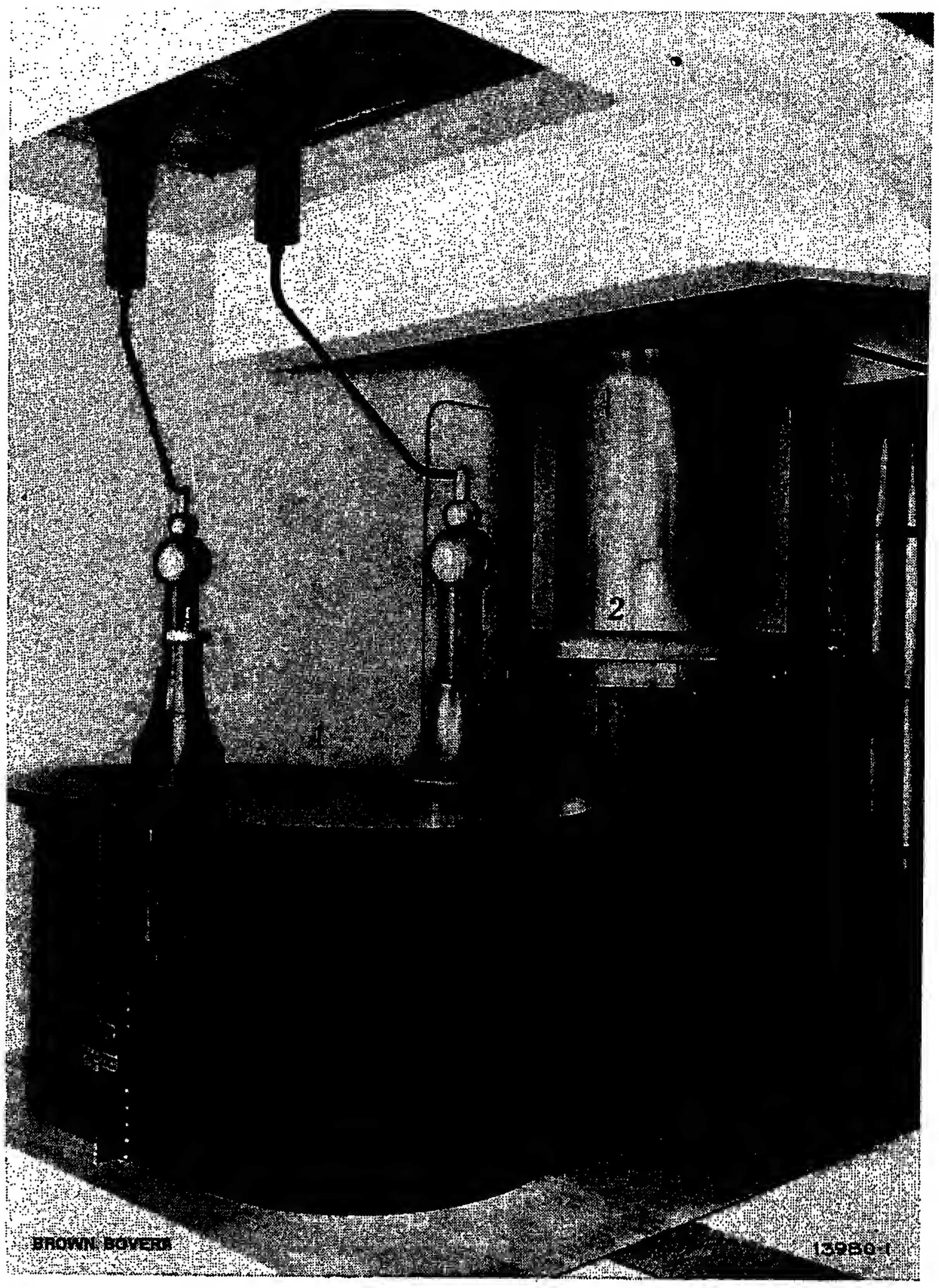


Fig. 11. — Part of the cellar below the dark room.
1. Testing transformer for 225 kV.
2. Air-gap condenser with variable capacity.

Immediately below the dark room is the cellar in which are housed the oil tank referred to and the testing transformer with its induction regulator (Fig. 10). This transformer has an output of 200 kVA with a ratio of 700/350'000 V when one high-tension terminal is earthed, and of 1000/500'000 V with both high-tension terminals insulated. It is erected so that its cover is on the same level as the floor of the dark room, above which only the insulators project. The

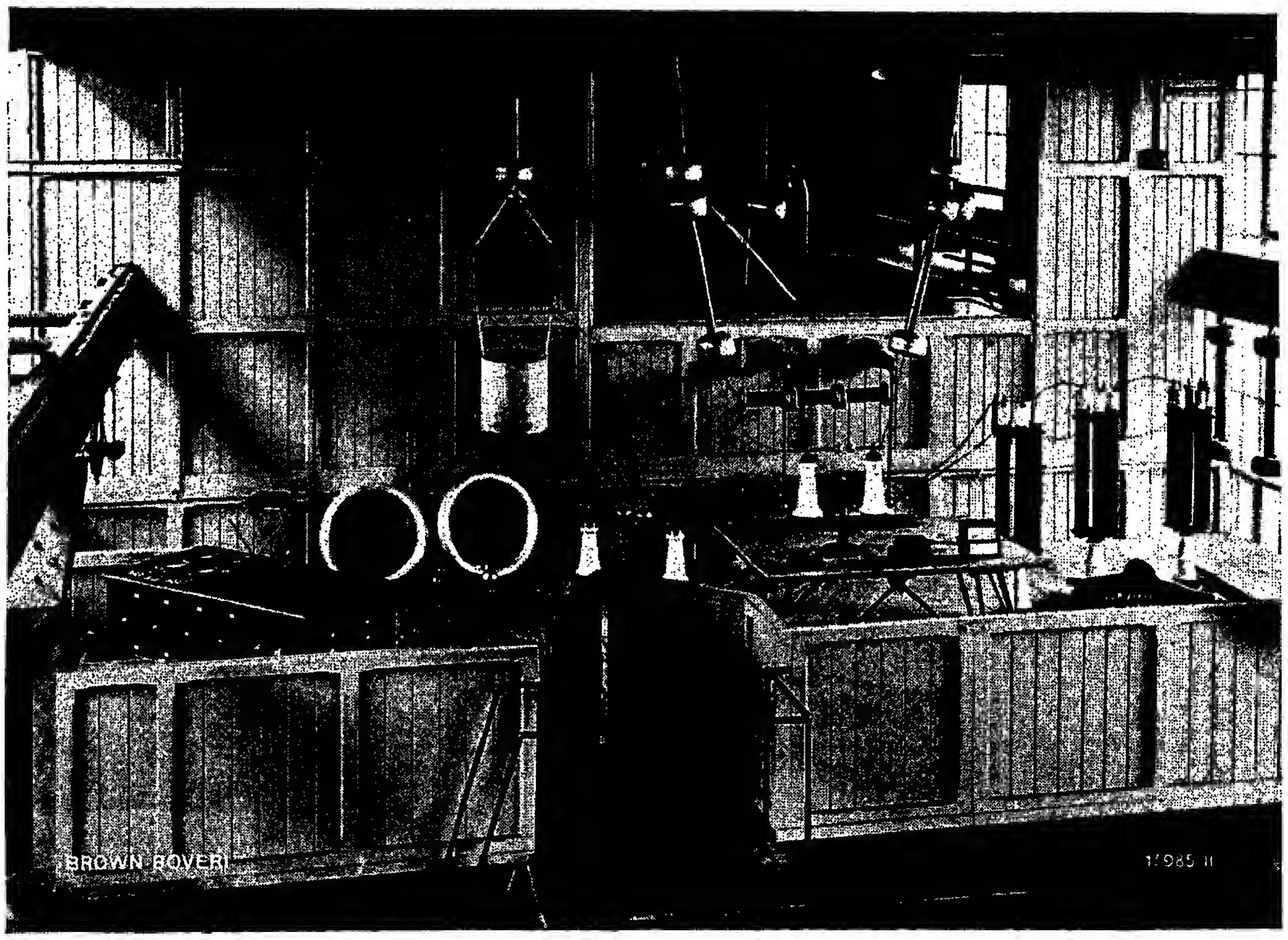


Fig. 12. — Pressure-surge test room, looking towards the dark room.

spark gap, used for testing purposes, is directly connected to the high-tension winding and is normally fitted with spheres of 500 mm diameter, although others of 250, 125 or 62·5 mm can be employed if necessary.

The pressure at the testing transformer can be gradually increased from zero to the desired maximum by means of the induction regulator, to which an unregulated pressure is supplied, either from the step-down transformer in the machine room at 380 V, or from any of the alternators. It is also possible to work with any alternator connected directly to the low-tension side of the testing transformer. The induction

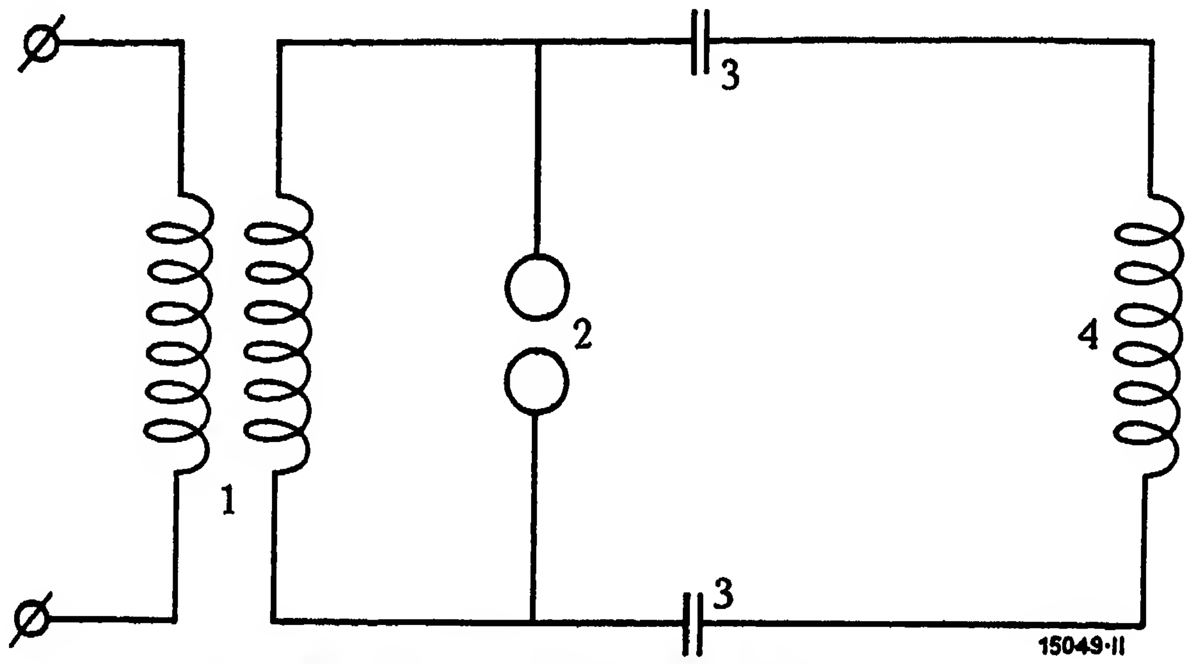


Fig. 14. — Diagram of an oscillatory circuit.

1. Testing transformer. 2. Sphere spark gap. 3. Condensers. 4. Object under test.

regulator can be adjusted by remote control, or the pressure of the alternator can be regulated by altering its excitation—in both cases from the dark room. The observer's stand is to the right as seen from the entrance, so that he has the whole of the dark room before him. A gallery is also provided from which observations can be made in safety (Figs. 13 and 15).

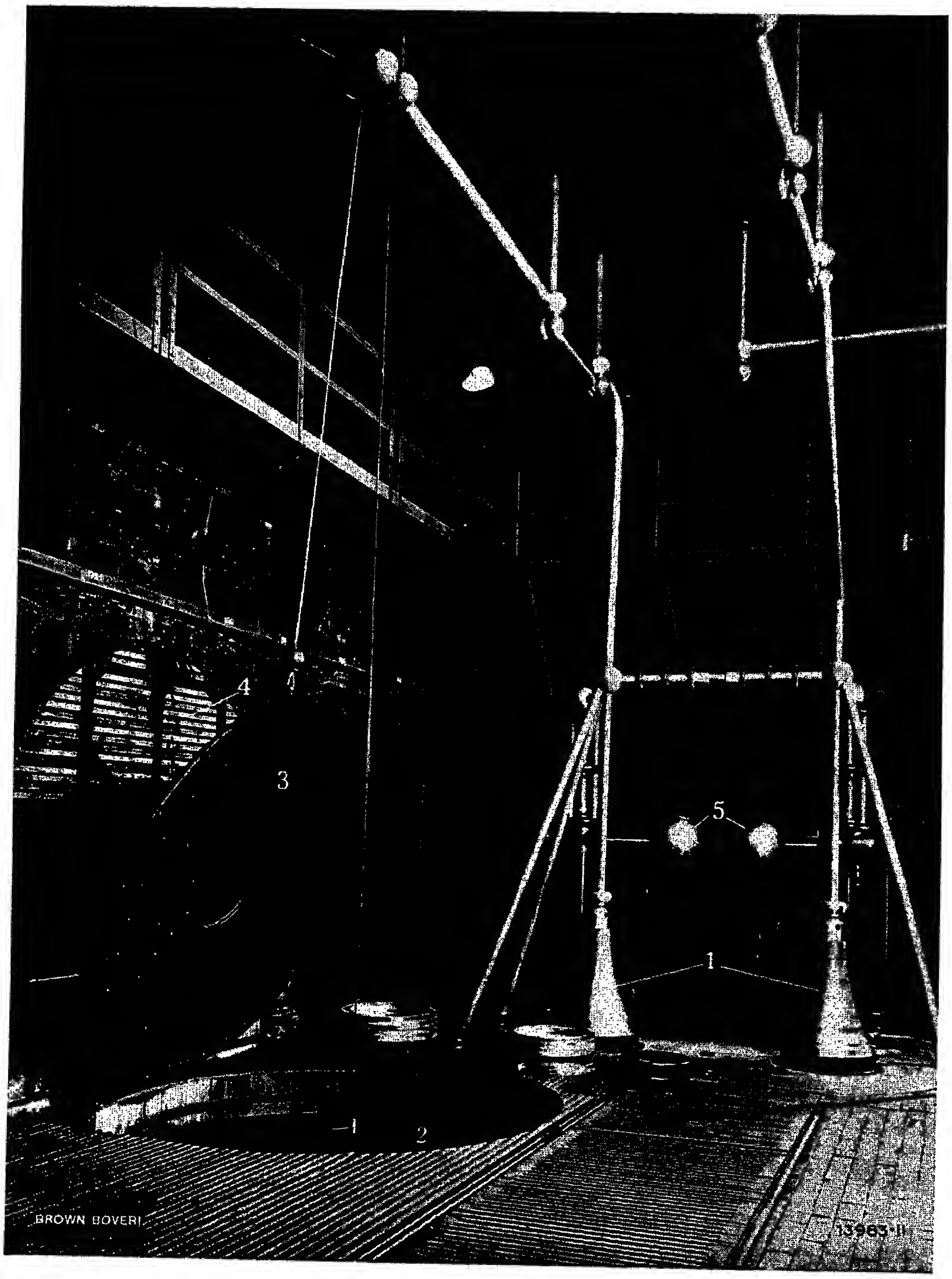


Fig. 13. — Interior of the dark room with oil tank open.

1. Terminals of 500-kV testing transformer.
2. Oil tank.
3. Sheet-steel cover.
4. Wooden grid.
5. Spark gap with spheres 500 mm in diameter.

In Fig. 11 is shown a second testing transformer having an output of 50 kVA, and a ratio of 500/150'000 V with one terminal earthed, and of 750/225'000 V with both terminals insulated. It is situated in the same cellar as the transformer already described. Both transformers can also be used for supplying either section of the testing bay for standard measurements, or the room for pressure-surge tests. Permanent conductors are laid for this purpose, the arrangement of which can be seen in Fig. 12.

Fig. 13 shows part of the dark room with the oil tank open for the testing of distance rings for high-tension transformers. An oil tank is necessary for all tests on materials for high-tension transformers, whether it is the determination of the breakdown pressure between two insulated conductors, the testing of the distance rings which separate the windings from the iron, or of the insulating tubes which separate the low and high-tension windings from each other. In all cases the object in question must be kept immersed

in oil throughout the test if correct results are to be obtained. Moreover, an oil tank is indispensable where insulators for outdoor transformers and oil circuit breakers are to be tested.

The tank is a cylinder, 2·6 m in diameter and 2·4 m deep, with a movable wooden floor fitted inside it to carry the objects under test.

During the tests, the cover shown in Fig. 13 is closed. It is of double sheet steel, with an air space to prevent condensation of moisture on the lower surface when tests are made under rain conditions, the upper surface being cooled by the water from the sprinklers. A wooden grid is laid over this steel cover so that the floor remains quite level.

Fig. 16 shows a 7000-kVA transformer for 8000/50'000 V being taken into the dark room for making observations on brush-discharge effects.

VI. PRESSURE-SURGE TEST ROOM.

The progress in high-tension technology recorded during recent years is by no means purely the result of theory, but has depended to an equal extent upon exhaustive experimental and testing work. For some years, Brown, Boveri & Co. have employed a special research staff, working mainly on high-tension phenomena, and particularly on the investigation of means for preventing, or at least minimising, disturbances in high-tension plants.

This work can be divided into the following sections:—

1. Experiments connected with surges and overpotentials to earth.
2. Excess-current tests.
3. Tests on apparatus for protection against overpotentials (Horn lightning arresters, choke coils, extinction coils, etc.).
4. Measurement of losses in insulating materials using a special high-pressure wattmeter.

It is self-evident from this list that such work necessitates extensive apparatus and experimental equipment. The new transformer testing department includes a special room for experiments on pressure surges, containing apparatus with which it is possible to make insulation tests with high-frequency current.

It often happens that, due to switching operations, earthing, or winding defects, pressures arise which may seriously threaten the insulation of the machines and transformers. The testing of winding material under such working conditions is not possible with the normal insulation tests carried out in the dark room. The arrangement of connections shown in Fig. 14 is

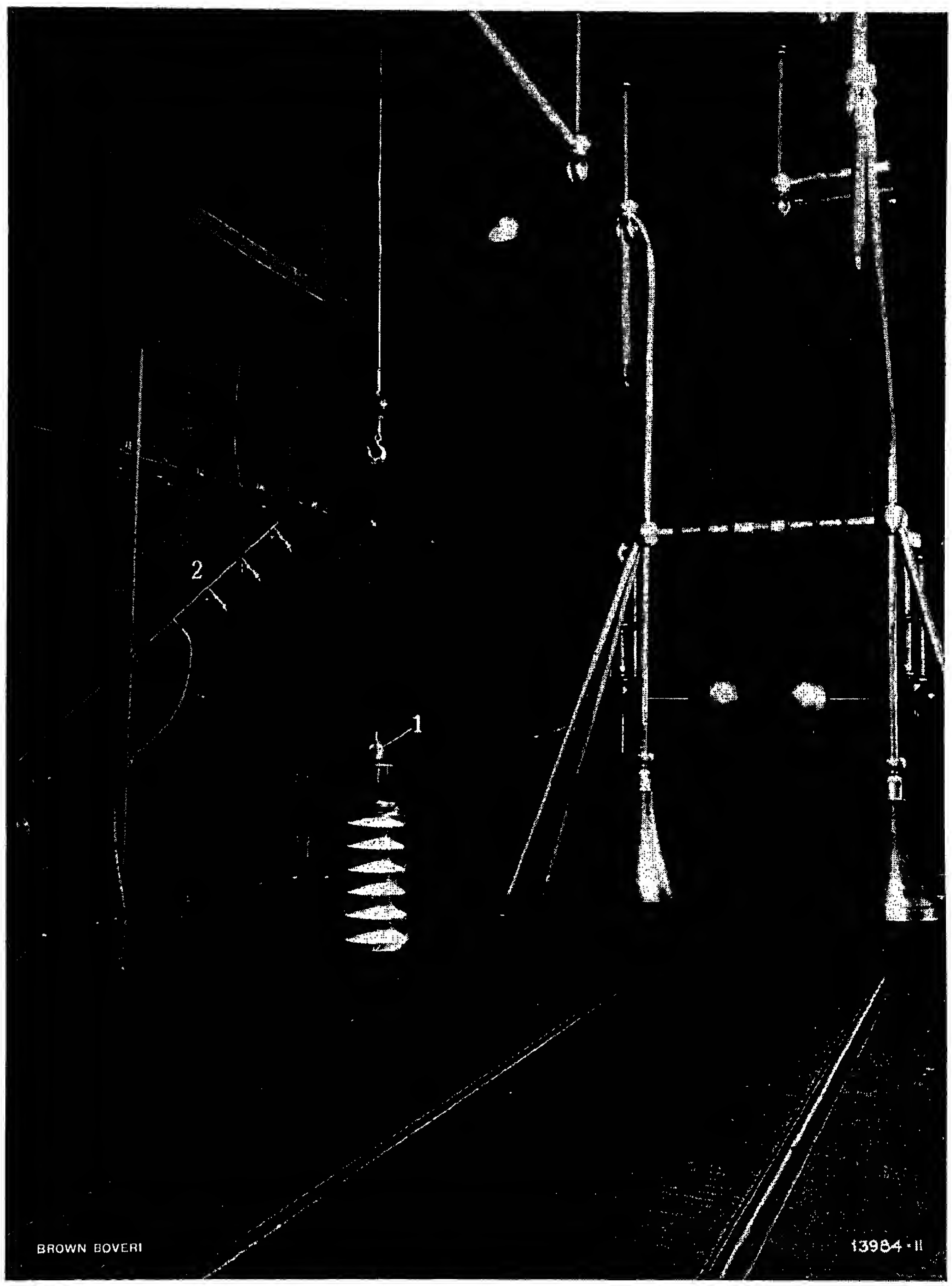


Fig. 15. — Interior of the dark room with a terminal bushing for outdoor use mounted in the oil tank.

1. Flashover test on an oil-filled bushing for 110 kV.
2. Sprinkler apparatus.

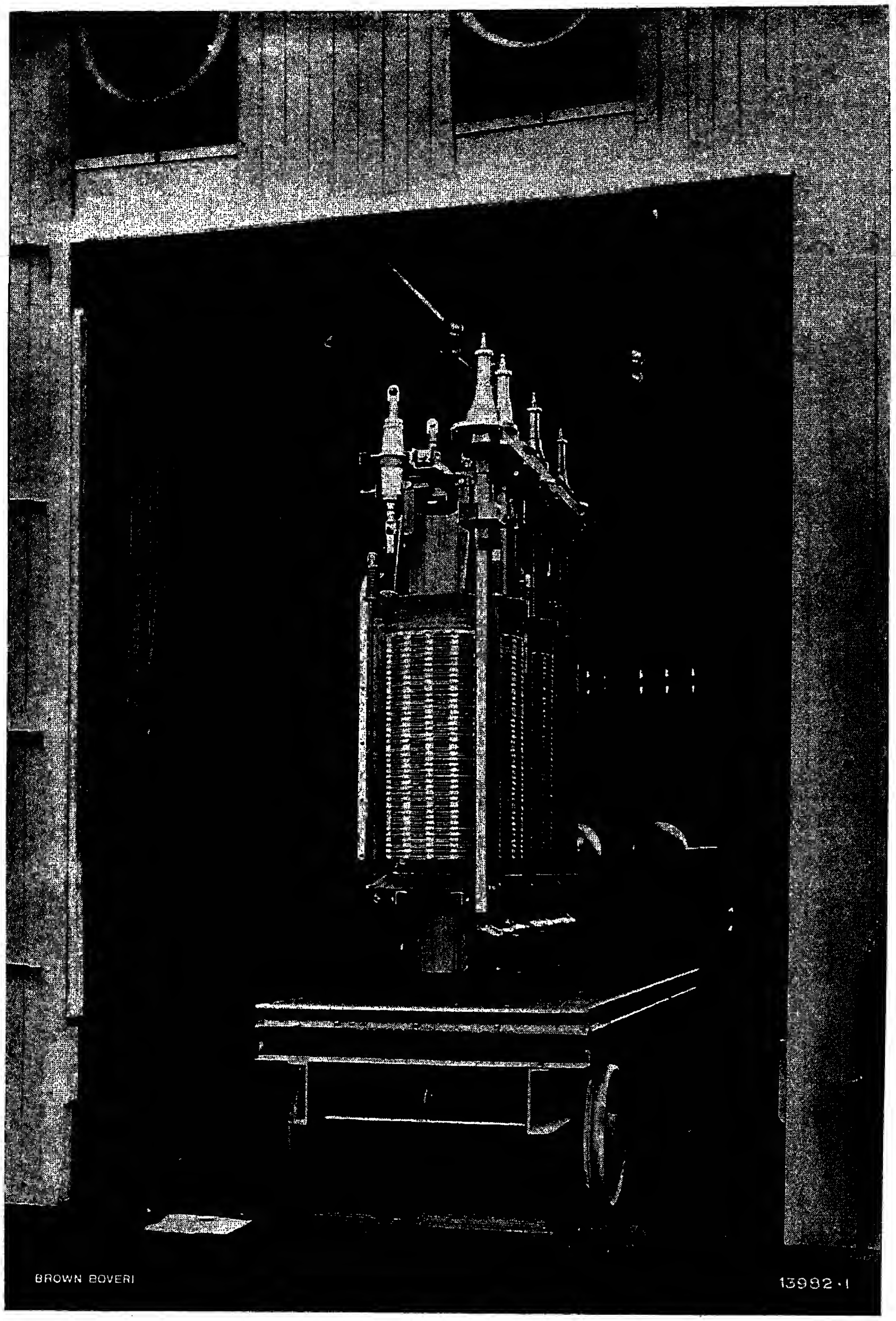


Fig. 16. — Entrance to the dark room.

Fig. 17. — Flashover test on an oil-filled bushing as used for outdoor transformers and oil circuit breakers.

frequently adopted for these tests, and is generally referred to as an oscillatory circuit.

It is not proposed here to deal with these investigations in any further detail, but the equipment of the pressure-surge test room will be outlined. This room is next to the dark room, as can be seen in Fig. 12. The leads from both the 500'000-V and the 225'000-V testing transformers are so arranged that they can be connected to the test room as required by means of knife switches.

The pressure of the testing transformers can be regulated from two places by their induction regulators. Fig. 12 shows the switch desk and other arrangements for surge tests, which are mounted on a raised platform. The leads to the dark room can be seen in the background through the opening in the wall.

A second testing set, chiefly used for the measurement of losses by a high-tension wattmeter, is situated in the testing section for small transformers on the ground floor.

The pressure of any of the alternators can be regulated as desired from either of these testing sets.

Ed. Lienhard. (G. T. S.)

Published by BROWN, BOVERI & CO., BADEN (Switzerland). Printed by Kreis & Co., Basle.

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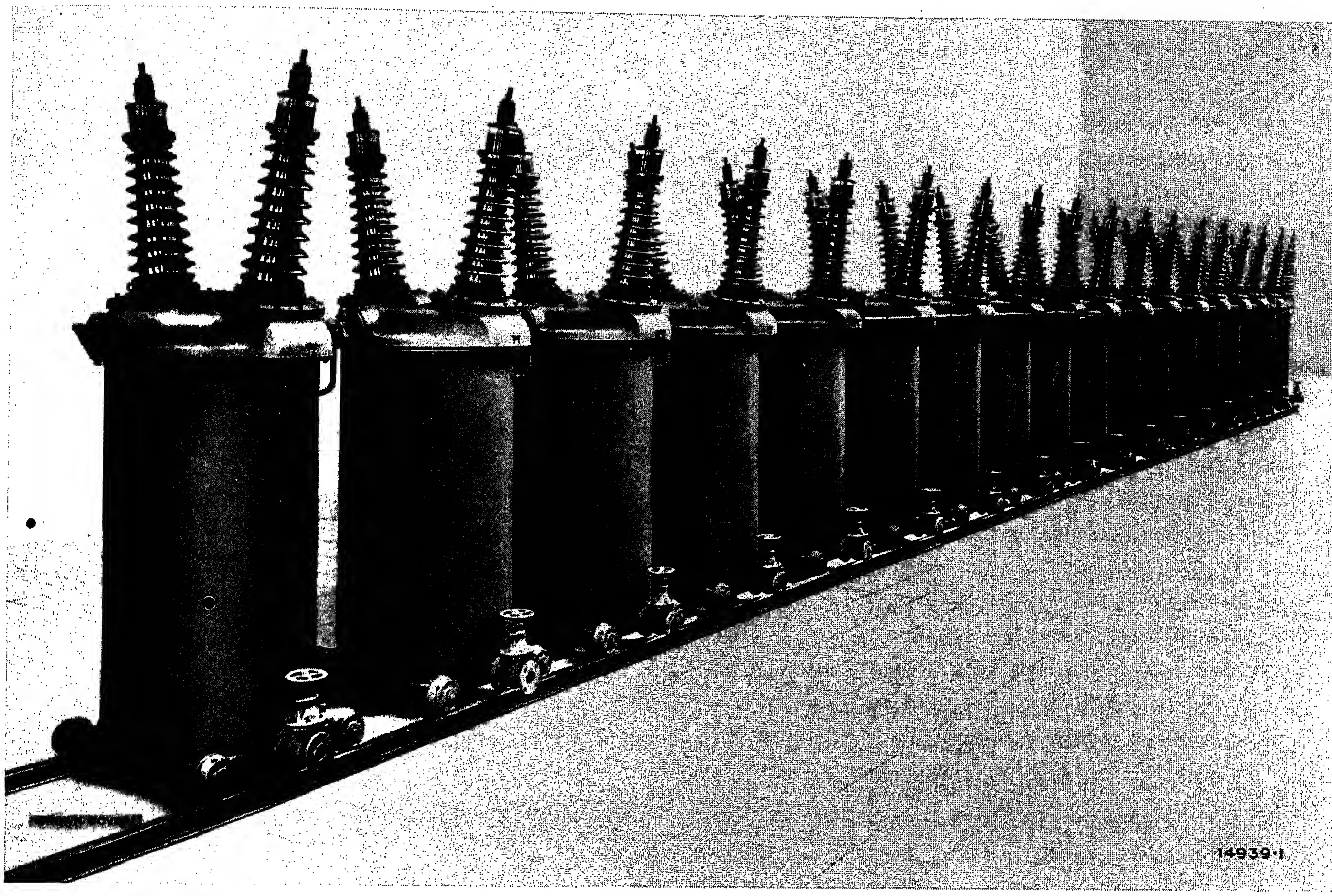

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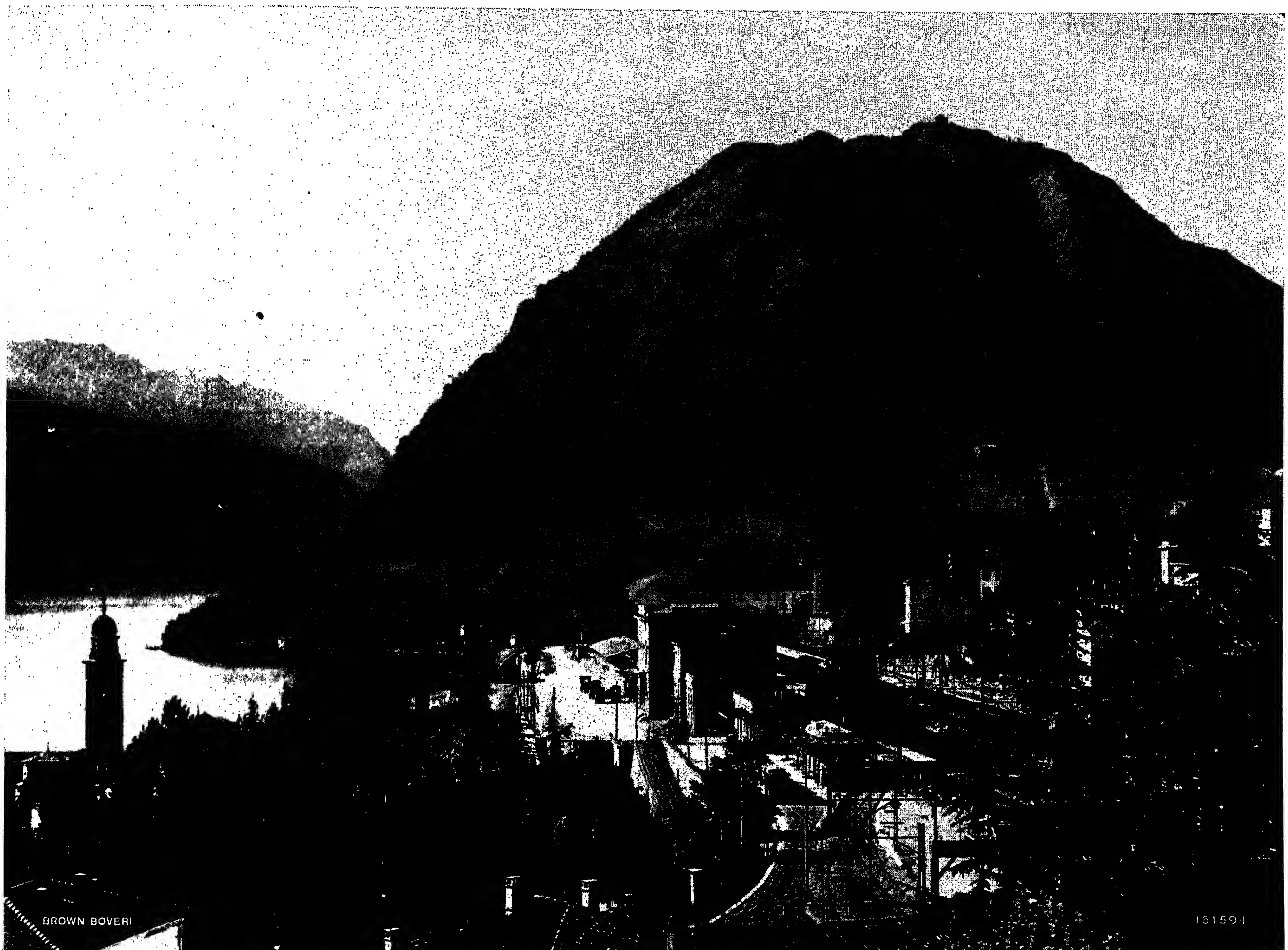
VOL. XI JANUARY, 1924 No. 1

THE BROWN BOVERI REVIEW

EDITED BY BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND)



ELECTRIFICATION OF THE SWISS FEDERAL RAILWAYS. LUGANO RAILWAY STATION.

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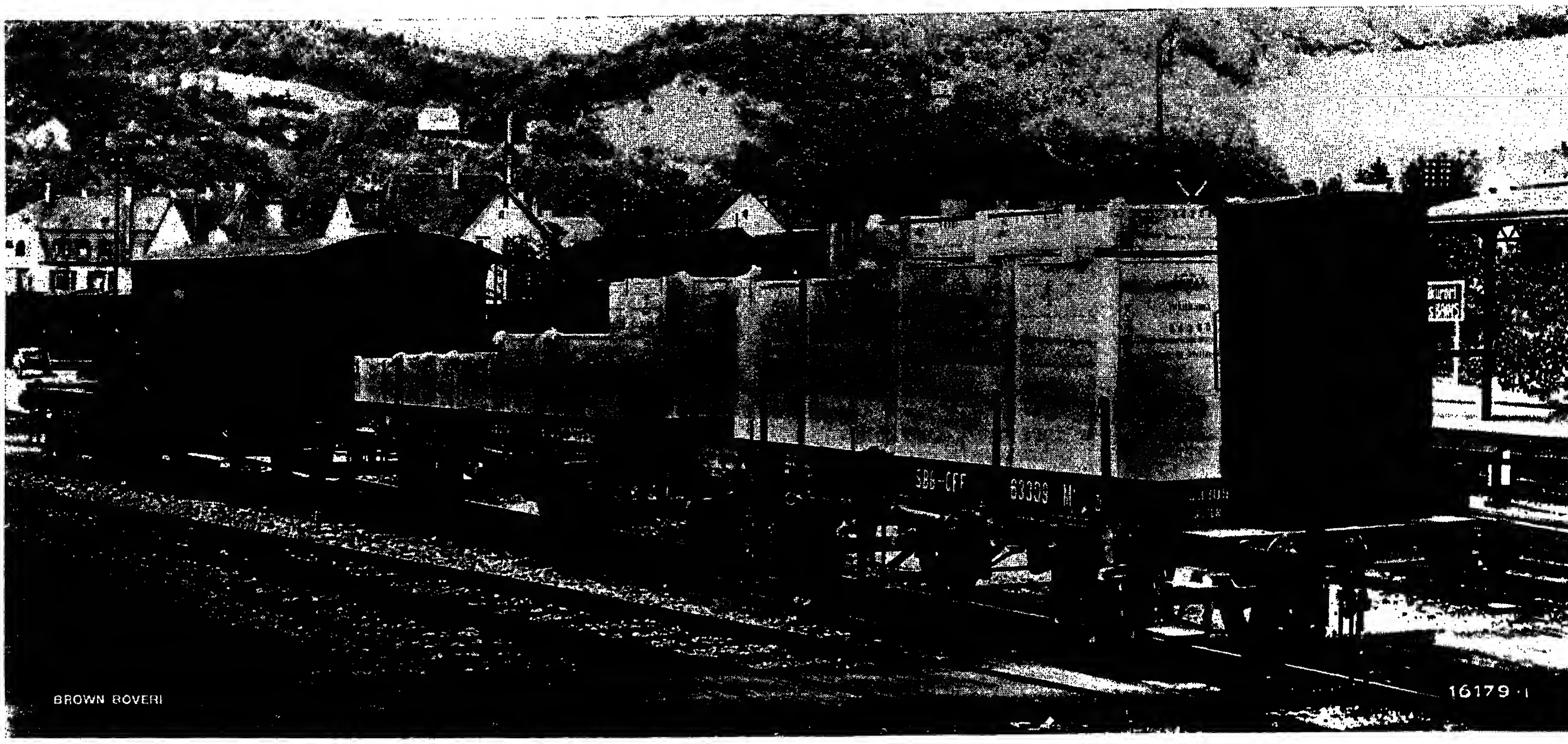
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THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND)

VOL. XI JANUARY, 1924 No. 1

The Brown Boveri Review is issued monthly. Single numbers: 1.20 francs (1 shilling). Yearly subscription: 12 francs (10 shillings).

THE GENERATING EFFECT IN ROTARY CONVERTERS ON SHORT CIRCUIT.

Decimal index 621. 313. 53.

Summary.

THE following article deals with short-circuit tests carried out on one of a series of rotary converters built for direct-current traction service at 1600 V, a new type of quick-acting circuit breaker being employed. The retardation of the armature was measured by means of a torsiograph, and the energy given up by the armature when generating — i. e., converting mechanical energy to electrical energy — during the short circuit was determined. This energy corresponds practically to that absorbed by the short circuit. The variations in the speed of the armature during the short-circuit period are calculated approximately.

The exceptionally favourable behaviour of these rotary converters on short circuit is ensured by the employment of Brown Boveri patent commutating poles and the quick-acting circuit breaker. Their absolute reliability under railway conditions is very effectively demonstrated by the large number of times it is possible to short-circuit a converter without giving rise to trouble of any kind.

I. INTRODUCTION.

IN an article on "1500-volt rotary converters for direct-current railways" in The Brown Boveri Review, 1922, No. 8, various particulars are given of a rotary converter for direct-current pressures up to 1650 volts, the output being 750 kW continuously, 1125 kW during two hours, and 2250 kW during five minutes following on a run at full load. It was mentioned that very complete tests, especially as regards ability to withstand short circuits, were carried out in the works on the first of a series of seven rotary converters with the above output, which were built for the Midi Railway Company in France. The number of times this first machine was short-circuited, either completely or across a very low resistance of 0·2 ohms or even less, was given as 150. Subsequently, however, the total number of short circuits was increased to about 400 during a special study regarding certain technical questions. Such severe testing of plant has probably seldom been carried out, and almost certainly never been called for by a purchaser. In the case in question, it was certainly not out of place, as it demonstrated the fallacy of the opinion, held until recently by many engineers, that rotary converters for 50-cycle railway supply could only be considered reliable up to about 1000 volts.[1]

II. ARRANGEMENTS FOR THE TESTS.

For making the short-circuit tests, the arrangement shown in Fig. 1 was generally adopted. The quick-acting circuit breaker S was closed before the direct-current end of the machine was short-circuited. The short was made at K either by closing a contactor electrically, or by simply inserting a copper blade by hand into a contact jaw composed of two suitably shaped copper strips insulated from one another, and connected one to the positive and one to the negative pole of the converter. The blade was provided with a handle of such dimensions that

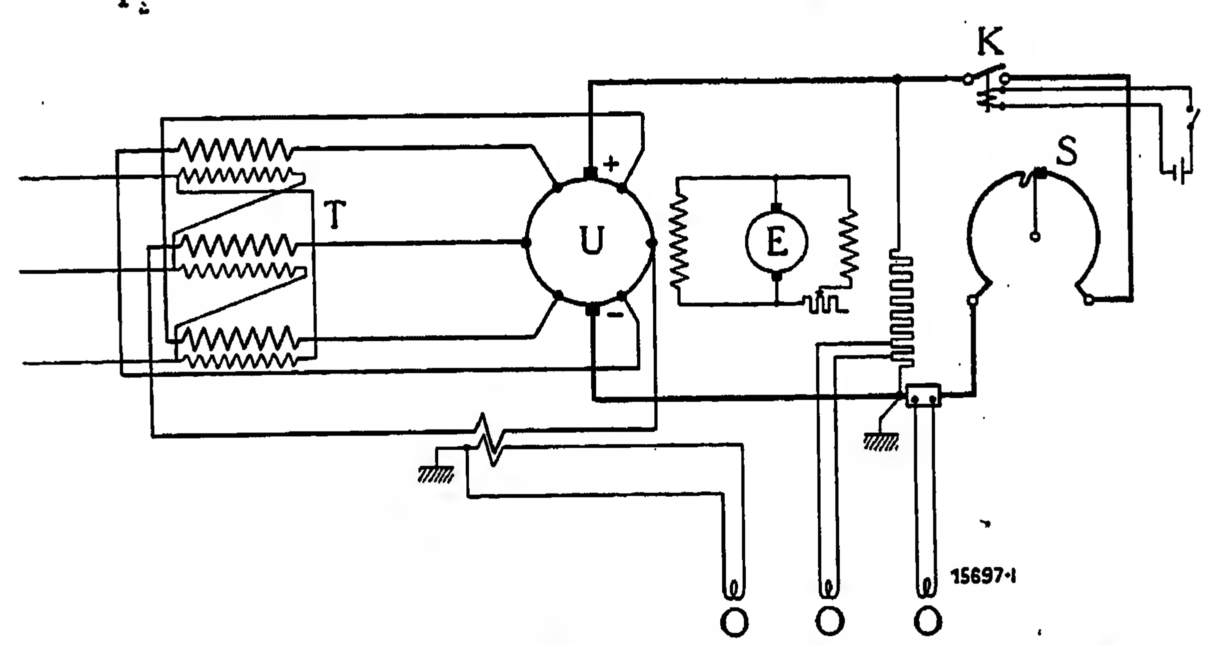


Fig. 1. — Diagram of connections for the short-circuit tests.

U. Six-phase converter.
E. Built-on exciter.
S. Quick-acting circuit breaker.
K. Contactor.
T. Transformer.
O. Oscillograph coils.

the operator could produce the short circuit without risk. The current was then interrupted by the quick-acting circuit breaker S in series with the short circuit. This apparatus was one of a number of breakers constructed under the same contract as the rotary converters, some being intended for use as machine breakers and some as feeder breakers. They are designed to switch out a short circuit in 0·015—0·02 sec,

[1] See The Electrician, March 3, 1922.

this time being reckoned from the moment the short occurs till the current is completely interrupted.

For taking oscillograms, a device was employed which put the oscillograph in and out of action automatically at the correct instant.

In order to permit the variations in the speed of the converter armature to be observed during the short circuit and immediately afterwards, a *torsio-*

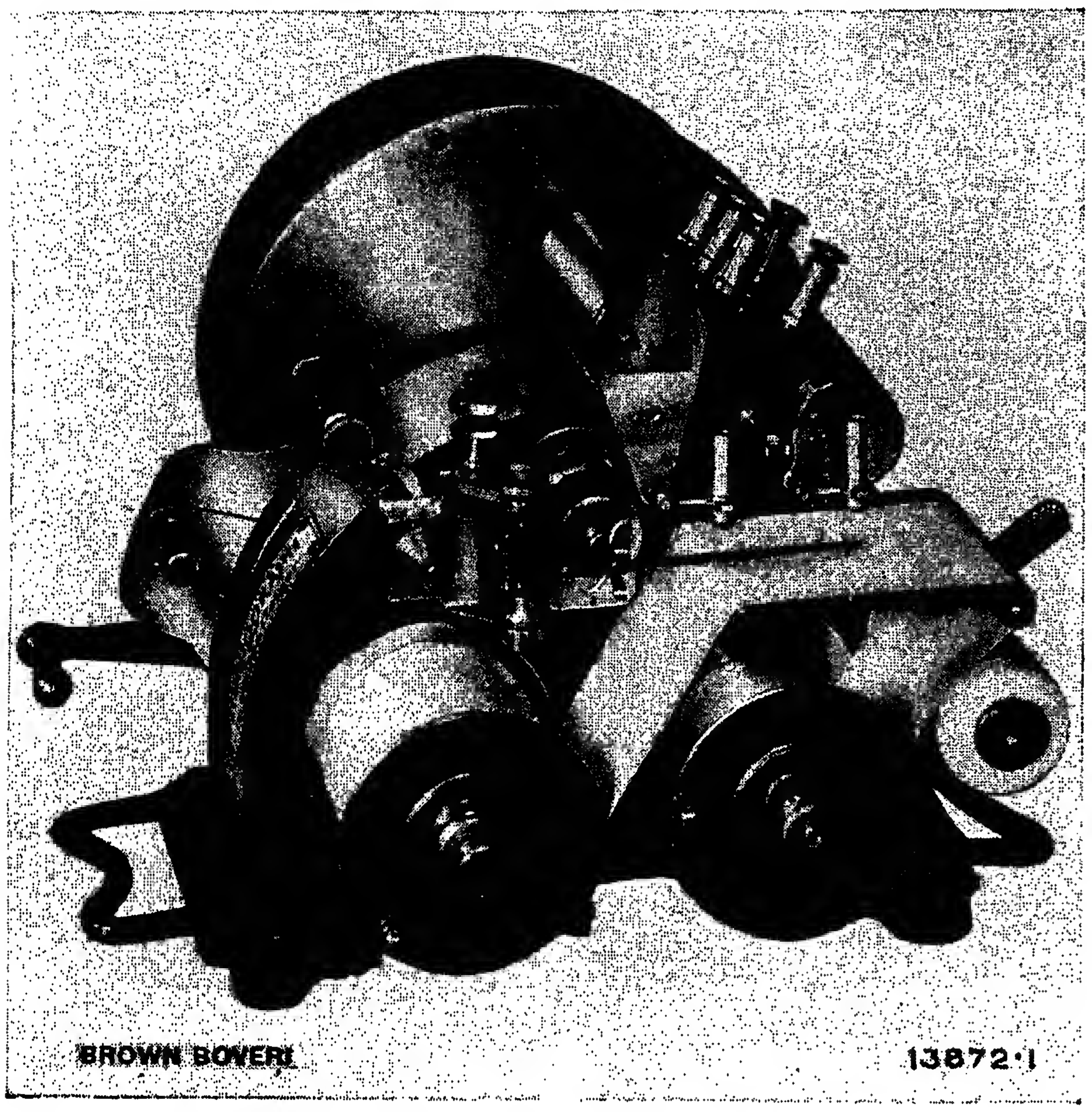


Fig. 2. — The Geiger torsiograph.

graph[1] (Fig. 2) was used. This apparatus was connected to the shaft of the converter by a tight band with as little elasticity as possible, which served as a belt drive. The rotary movement of the converter was thus exactly transmitted with every variation to the extremely light pulley on the torsiograph. Inside this pulley there is a flywheel, the inertia of which is relatively great. This is carried independently on small ball bearings and connected to the pulley in a very elastic manner by means of a spiral spring. The movement of the flywheel relative to the pulley is limited by stops. With large variations in speed, the flywheel is carried round by the stop, and only comes back to its normal position under the influence of the spring when the belt speed again becomes steady. If the armature of the converter is retarded or accelerated, the pulley of the torsiograph moves relatively to the flywheel, and the *difference of travel,* or rather the difference in the angle passed through, is recorded by suitable means on a strip of paper travelling at constant speed, on which the time is also recorded. The torsiogram is a curve showing as ordinates the difference in the angular movement of the flywheel and the pulley, with time as abscissæ.

The relation between the moment of inertia of the flywheel and the force exerted by the spring is so chosen that the flywheel cannot follow rapid changes in the driving speed, but retains its steady rotation; the curve drawn therefore represents truly the changes of speed occurring. When the change of speed takes place more slowly, that is to say, when the periodicity of the variations approaches the natural frequency of the moving system of the torsiograph, a true curve is not obtained. In such cases, it is necessary to interpret the torsiogram with care, and to consider how far the curve drawn varies from the real conditions. The natural frequency of the torsiograph was found to be 2·12 vibrations per second.

III. THE KINETIC ENERGY OF THE ARMATURE ON SHORT CIRCUIT.

The question arose on the occasion of the short-circuit tests: — To what extent is the short-circuit energy supplied by a generating effect in the rotary converter?

The importance which the behaviour of the machine as a generator — as distinguished from its normal duty as a converter of electrical energy — has on the commutation or flashing at the brushes, when a short circuit occurs on the direct-current side, was pointed out in a previous article.[1] It was by recognising this that Brown, Boveri & Co. arrived at their special design of commutating poles for rotary converters, which is patented by the firm[2].

Any output from the machine as a generator can only be obtained at the expense of the kinetic energy stored in the rotating parts, with a corresponding reduction of speed. The possibility of an output of any importance resulting from the relatively small amount of energy stored in the field system is here neglected.

Considering that the whole short-circuit process is finished in about 0·016 seconds by the quick-acting breaker, it is to be expected that, with the relatively large amount of kinetic energy stored in the armature, only a small retardation of the latter would be necessary to provide the whole electrical energy of the short circuit.

[1] Cf. Zeitschrift des Vereins Deutscher Ingenieure, 1916, p. 811 ff.: Dr. Ing. Jos. Geiger, "Der Torsiograph, ein neues Instrument zur Untersuchung von Wellen".

[1] See Revue BBC, 1915, No. 12.

[2] See brochure 783E: "Rotary converters. The effect of direct short circuit on the direct-current side."

The flywheel effect (GD^2) of the armature is 3300 kgm², the polar moment of inertia $J = \frac{GD^2}{4\,g}$ is therefore 84 kgm². At the normal speed of 750 r. p. m., that is, with an angular velocity

$$\omega_0 = \frac{\pi \cdot n}{30} = 78{\cdot}5,$$

the stored energy

$$A = \frac{J \cdot \omega_0^2}{2} = 252'000 \text{ mkg}.$$

A reduction ω' in the angular velocity of say 2% corresponds to about 4% of energy given up, which amounts to A = 10′080 mkg. This represents, in the time t = 0·016 seconds, an average output given by:

$$N = \frac{10'080}{0{\cdot}016} = 630'000 \text{ mkg per sec} = 6200 \text{ kW},$$

with a drop in the angular velocity of

$$\omega' = 0{\cdot}02\,\omega_0 = 1{\cdot}57.$$

If this fall in speed is looked upon as being a supplementary negative angular velocity, its value will be 0 when the short circuit commences, and 1·57 when it is interrupted. With t = 0·016 sec, the lagging of the armature behind its normal speed of rotation amounts therefore to

$$\gamma = \frac{1{\cdot}57 \times 0{\cdot}016}{2} = 0{\cdot}0125 \text{ radians}$$

or 0·715 degrees, which corresponds to 2·86 electrical degrees with a converter having p = 4, that is, four pairs of poles.

This shows that, on account of the great rapidity with which the circuit is broken, there can be no question of the rotary converter falling out of step as a direct result of the short circuit, even if the latter is as heavy as 6200 kW (i. e., an average current of 3900 A at a pressure of 1600 V). It should be mentioned, however, that the danger of falling out of step is not eliminated upon the breaking of the circuit, since the armature has a certain slip, and its angular displacement measured electrically with respect to the magnet frame is still increasing. It is the duty of the synchronous torque, and especially also of the asynchronous torque, which is exerted by reason of the damping winding of the field poles, to accelerate the armature and bring it again up to synchronous speed before it falls out of step.

IV. THE MAGNITUDE OF THE ELECTRICAL TORQUES DURING SHORT CIRCUIT.

If the drop in the armature speed, that is, the variation in the slip during the short circuit, is known, it is possible to determine, in at least an approximate manner, the value of the *asynchronous torque* from the particulars of the damping winding. The latter can be looked upon as being a symmetrical squirrel-cage winding, the slip as a function of the torque being calculated in the usual way. Alternatively, the slip can be measured by running the converter and loading it as an induction motor. With the machine tested, it was found that the slip S_1 was approximately 0·035 (i. e. 3·5%) when the converter had to develop normal torque $M_1 = 975$ kgm. As the slip can be taken as proportional to the torque, the asynchronous torque for slip S will be

$$M_a = \frac{975}{0{\cdot}035} \cdot S$$

In terms of the decrease ω' of the speed of rotation, since $S = \frac{\omega'}{\omega_0} = \frac{\omega'}{78{\cdot}5}$, the asynchronous torque is

$$M_a = \mu_a \cdot \omega'.$$

$$\text{where } \mu_a = \frac{975}{0{\cdot}035 \times 78{\cdot}5} = 350.$$

With a slip of 2%, that is $S = 0{\cdot}02$, $\omega' = 1{\cdot}57$, the torque becomes $M_a = 350 \times 1{\cdot}57 = 550$ kgm.

The power corresponding to this torque is

$$N_a = M_a\,\omega = M_a\,(\omega_0 - \omega') = 550\,(78{\cdot}5 - 1{\cdot}57)$$
$$= 42'300 \text{ kgm per sec} = 415 \text{ kW}.$$

The *mean* power generated during the period in which the slip increases from 0 to 2%, amounts, therefore, to about 200 kW. The mean value cannot be given exactly, since the increase of the slip as a function of the time is still unknown. The work done by the asynchronous torque during the time (t = 0·016 seconds) that the short circuit lasts will be roughly $A_a = 200 \times 0{\cdot}016 = 3{\cdot}2$ kWsec = 325 mkg.

From this it is seen that the *power* of the asynchronous torque *at the end of the short-circuit period* will be only a small fraction of the *mean* power due to the retardation of the masses, and that the *work* done by the asynchronous torque is negligible compared with the amount of kinetic energy given up by the armature. It is here assumed that the pressure on the alternating-current side remains constant.

The power of the *synchronous torque* during the short circuit will amount to even less than the above value. With a steady alternating pressure, it can be stated as

$$M_s = M_s' \cdot \sin p\gamma$$

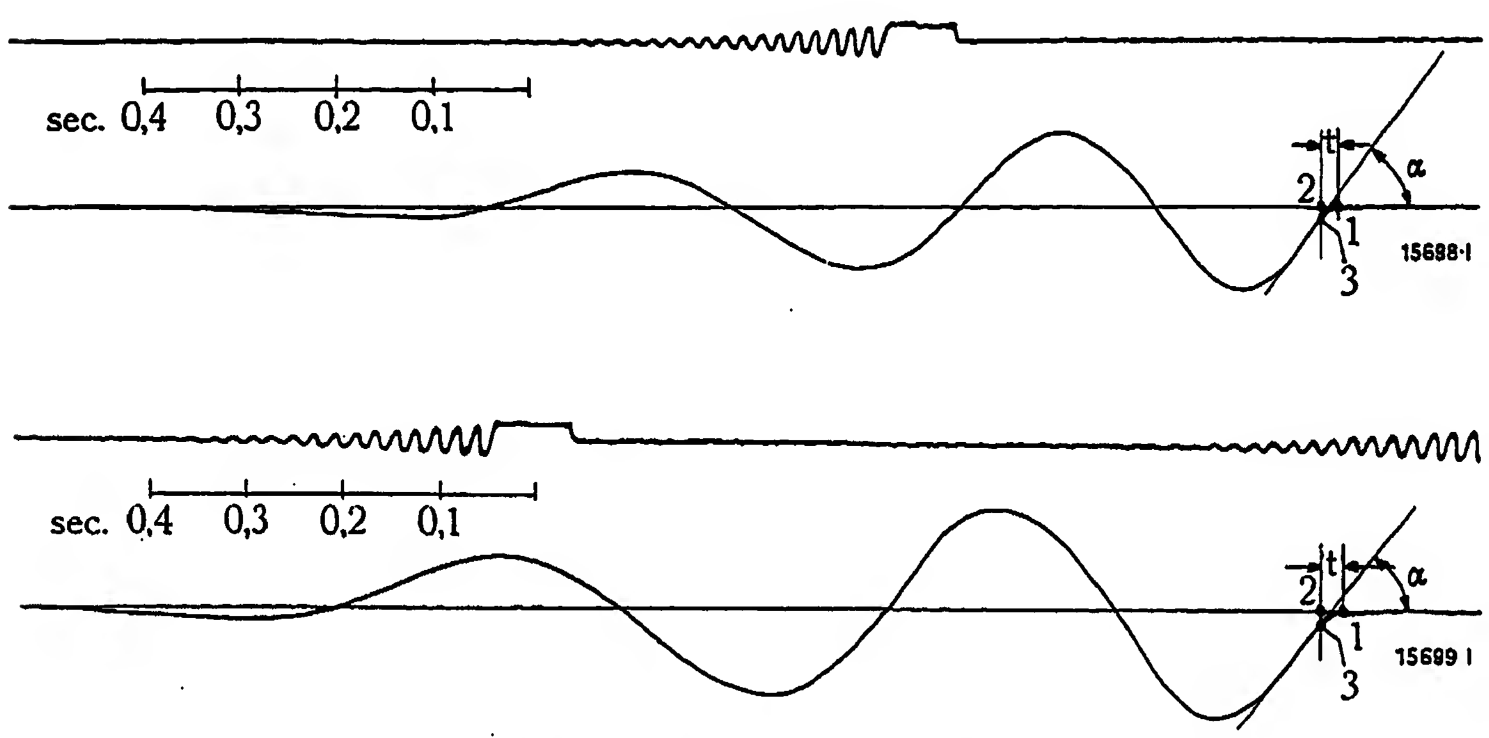
where γ is the angular displacement, p the number of pairs of poles, and M_s' the maximum synchronous torque that the converter can develop as a synchronous motor. Supposing the latter to be about three times the normal full-load torque, that is $M_s' = 3000$ kgm, and that $\gamma = 0{\cdot}0125$ radians $= 0{\cdot}715^0$ (see section III above), the synchronous torque at the *end* of the short-circuit period is

$$M_s = 3000 \times 4 \times 0{\cdot}0125 = 150 \text{ kgm.}$$

It suffices in this case to take the sine as being the same as the arc. The power corresponding to this value for M_s is

$$N_s = M_s\,(\omega_o - \omega') = 150 \times 76{\cdot}9 = 11'500 \text{ mkg per sec} = 113 \text{ kW},$$

which is considerably lower than that for the asynchronous torque.



Figs. 3 and 4. — Two torsiograms taken during short circuit.

These approximate figures for the power due to the synchronous torque refer to the instant at which the short circuit is interrupted, and it by no means follows that this torque does not increase *after* the short circuit has been cut off. As the armature has a certain slip at the instant in question, its angular displacement reckoned electrically with respect to the field magnets is increased, which means a further rise in the synchronous torque. The latter is, however, still relatively small, and as the slip does not become greater after the short circuit is interrupted, the asynchronous torque does not increase any more; hence it follows that the displacement will become quite considerable before the synchronous torque, together with the slowly decreasing asynchronous torque, suffices to prevent any further increase in the displacement of the armature. The displacement ceases to increase and reaches its maximum value only after the armature has come up again to synchronous speed under the action of the electrical torques. This occurs when the work done by both torques, after the interruption of the short circuit, has become equal to the kinetic energy given up by the armature during the short-circuit period. At this instant the synchronous torque is a maximum, and the armature will be accelerated *above* the synchronous speed of rotation until the asynchronous torque, which now acts in a braking manner, becomes equal to the now decreasing synchronous torque. The increased speed enables the armature to recover the distance it has lost, and even to exceed it to a certain extent, so that hunting of the armature about its normal position is set up. The stronger the asynchronous torque, the more rapidly will the oscillations be checked.

The conditions in the machine *after* the circuit has been opened will not be gone into more fully here. It may be mentioned, however, that it is most important to cut off the short circuit as quickly as possible, owing to the fact that the kinetic energy lost by the armature on account of the short circuit must be completely made up by the electrical torques by the time the armature has attained its maximum displacement. If switching out is not rapid enough, the work expended on the short circuit would be so great that the armature would slip beyond the point corresponding to the pull-out torque, and flashing-over at the brushes would take place.

V. MEASUREMENT OF THE ENERGY GIVEN UP BY THE ARMATURE DURING THE SHORT CIRCUIT.

The torsiograms, Figs. 3 and 4, which are to be read from right to left, show the relative armature displacement resulting from the short circuit. The abscissæ are proportional to the time, while the ordinates are a function of the angular displacement of the armature relative to the position it would occupy at synchronous speed. If a tangent is drawn at any point in the torsiogram, its slope is a measure of the additional angular velocity, that is, of the difference between the actual speed and the steady synchronous speed. The speed of rotation of the armature is regular, and the relative angular displacement zero, up to the point 1, at which the short circuit begins. The maximum tangent of the first large displacement is drawn at point 3. It corresponds to the largest additional angular velocity which, being here negative, represents the lowest absolute speed of the armature. As expected, it was found that the time t from 1 to 2, as far as could be estimated with the small scale of the torsiogram, corresponds to the duration of the short circuit as

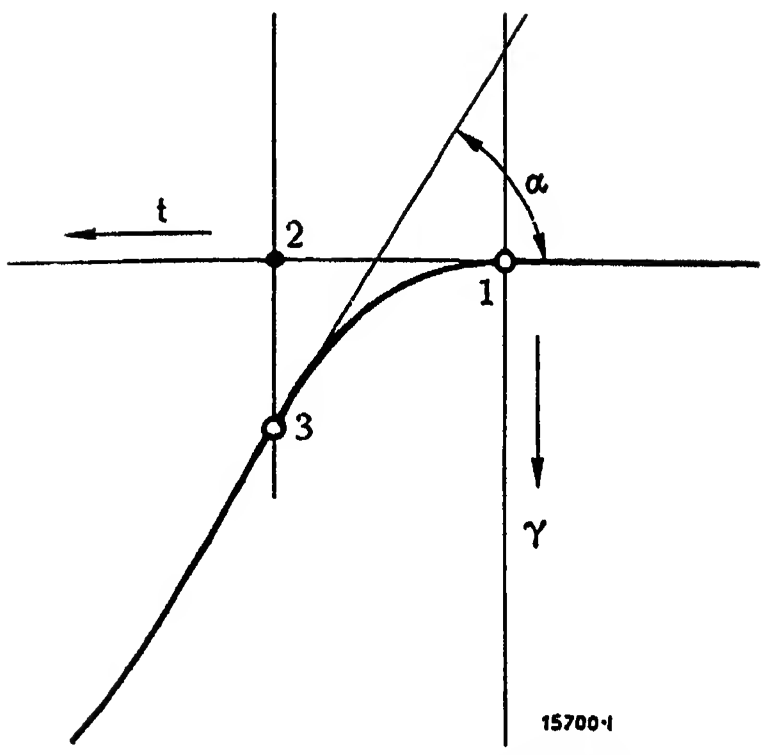


Fig. 5. — Angular displacement of the armature when the short circuit occurs.
λ. Angular displacement.
t. Time.

given by the oscillogram.

The records obtained by means of the torsiograph consist therefore of two parts, the first and shorter of which gives the conditions during the short circuit, while the second and longer portion represents the oscillation of the armature after the short circuit is interrupted. The slope of the tangent increases very rapidly in the first portion, which means that the additional angular velocity rises quickly from zero to the maximum amount. As will be explained more fully later, the process of the transference of energy while the short circuit lasts can be looked upon as part of a periodic oscillatory process having a frequency which is small compared with that of the torsiograph itself. From this, it follows that the record given by the latter is very nearly true to the actual conditions, both with respect to the angular displacement (ordinates) and to the additional angular velocity (tangent), that is to say, the correct proportion between the values is represented.

The angular displacement cannot be measured with the desired accuracy from the curve, but the maximum tangent can be drawn sufficiently exactly, and it is the latter which is important for determining the energy given up by the armature. The following table contains the values of the additional angular velocity ω' for five tests, and the corresponding work done, calculated from the maximum tangent.

The latter is given by the formula:

$$A = J\,\frac{\omega_0^{\,2} - \omega_1^{\,2}}{2} = J\omega'\left(\omega_0 - \frac{\omega'}{2}\right)\ \text{mkg},$$

and $J = 84\ \text{kg m}^2$,

where ω_1 is the angular velocity at the end of the short-circuit period.

From the table it is seen that in these tests a mean armature slip of 2% was produced, which represents on the average roughly 100 kWsec of work done by the armature. These tests exhibit,

Test No.	ω'	Slip %	Kinetic energy given up by the armature mkg	kWsec
27	— 1·525	1·94	9 920	97
28	— 1·505	1·92	9 820	96
138	— 1·49	1·90	9 740	95
139	— 1·68	2·14	11 000	108
141	— 1·76	2·24	11 450	112
Mean value	— 1·59	2·03	10 390	101·6

therefore, conditions as assumed in section III. The length of time during which energy is given up cannot be obtained to any close degree of accuracy from the torsiogram, as the scale is too small, and the points 1 and 3 (Fig. 5), where a horizontal line and the maximum tangent respectively touch the curve, are difficult to determine. When, however, the corresponding oscillogram (Fig. 6) is used, the time from the commencement to the finish of the short-circuit period can easily be measured. This time must be taken as that during which the armature gives up its energy; its average value is 0.016 sec. From this, the *mean* power corresponding to the kinetic energy lost by the armature is found to be about 6200 kW, as calculated in section III.

It is also impossible to determine the angular displacement at the end of the short-circuit period from the torsiogram, as the position of point 3 is uncertain. In section VII of this article it will, however, be shown how, by making certain assumptions that permit a simple treatment, it is possible to calculate mathematically the variations in the angular displacement and in the angular velocity, and, from these, the changes in the work done, and in the power given up.

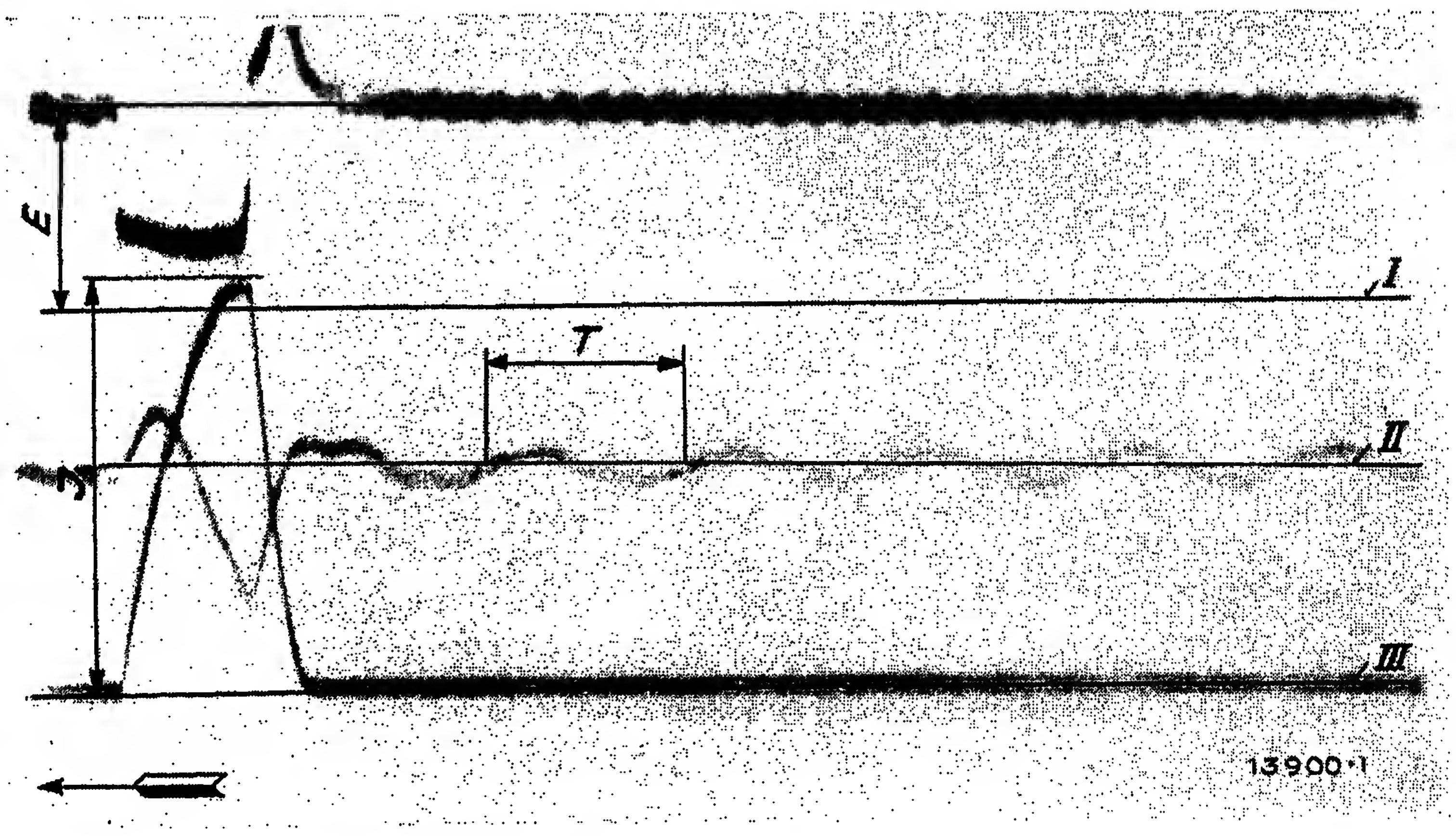


Fig. 6. — Oscillogram of a short circuit.

I. Zero line for direct-current presssure.
II. „ „ „ strength of alternating current.
III. „ „ „ „ „ direct current.

E = 1650 V.
J = 6200 A.
T = 0·02 sec.

Fig. 7. — Short circuit of a rotary converter provided with ordinary commutating poles.

VI. THE ELECTRICAL WORK OF THE ROTARY CONVERTER DURING THE SHORT-CIRCUIT PERIOD.

Obviously it is desirable to have information regarding the value of the electrical power taken from the machine by the short circuit, and the relation between this and the power measured as above. Since the power supplied from the alternating-current side—corresponding to the synchronous and asynchronous torques—during the short-circuit period is low compared with the power the armature actually furnishes, the electrical work on short circuit must be roughly equal to the kinetic energy given up by the armature. This work is composed of two parts: the *external* work and the *internal* work. The first of these can be determined easily by integrating the product of pressure and current for the duration of the short circuit. It was found that its value is in all cases decidedly *smaller* than the generating work of the armature. This is fairly obvious, since the pressure curve of the oscillogram represents the *external* pressure, which at once falls very considerably the moment the short circuit occurs. The pressure in question does not take account of the ohmic drop in the armature winding, in the commutating-pole coils, at the brushes, and in any cables that may be situated between the latter and the point where the pressure is measured. Instead of making a certain allowance for all these factors, and determining separately each of the two parts of the short-circuit work, it will be simpler to try to find the *total* work by integrating the product of the short-circuit current and the internal E. M. F.

The field of the rotary converter is at its full strength before the short circuit takes place, and, by reason of its inertia, tends to maintain the same strength during the short circuit. Since the duration of the latter is very brief, the field will not diminish to any great extent. As a rough approximation it is, therefore, possible to assume that the induced E. M. F. remains constant, considering also that the speed of the armature does not change appreciably.

If, therefore, the pressure *before* the short circuit occurs is multiplied by the mean value of the current *during* the short circuit, the product obtained is a measure of the total electrical work on short circuit. The data obtained from the oscillograms of the five tests previously referred to are as follows, the work corresponding to the kinetic energy given up being stated in the third column:—

Test No.	Electrical work on short circuit kWsec	Work done by armature kWsec	Difference %	Duration of short circuit in seconds
27	103	97	+ 6·2	0·0159
28	100	96	+ 4·2	0·0150
138	100	95	+ 5·3	0·0164
139	102	108	— 5·6	0·0163
141	120	112	+ 7·1	0·0220

On comparing the figures of the second and third columns, it is found that the average variation of the calculated values amounts to 5·8 %. If a slight allowance is subtracted for the electrical work corresponding to the drop of E. M. F. during the short circuit, the result of the tests can be taken to mean that *the short-circuit work is practically covered entirely by kinetic energy given up by the armature.* From this it does not follow that the current taken from the alternating-current mains is not subjected to considerable increases during the short-circuit period; this question is dealt with further on.

The fact that, on a short circuit, the rotary converter gives practically the whole short-circuit power operating as a generator rather than as a converter, results in an armature reaction sufficiently large to reverse the polarity of the commutating poles. This

effect is, however, counteracted effectively by employing the Brown Boveri patented type of commutating pole already mentioned, and which is characterised by large air-gaps in the body of the pole itself, and a winding with a correspondingly large number of turns[1].

VII. THE VARIATION OF ARMATURE SPEED DURING SHORT CIRCUIT.

As stated above, the small scale of the torsiograph records does not permit either the angular deviation or the additional angular velocity of the armature during the short circuit to be determined with any degree of accuracy. It may be possible, however, to calculate these as a function of the time sufficiently closely to represent adequately the movement of the armature, and the energy it gives up at every instant during the short circuit.

Curve 1, Fig. 9, shows the short-circuit current. For it is substituted a current i_s, of sine form (curve 2), which has the same arithmetic mean for the duration $\frac{T}{2}$ of the short circuit; its shape is therefore

$$i_s = i_1 \sin \tau t$$

where i_1 = the peak value of the equivalent sine current,
τ = the vectorial angular velocity of this current,
t = time.

When $\frac{T}{2} = 0{\cdot}016$ sec, the value of $\tau = \frac{2\pi}{T}$ is 200.

The short-circuit current is, therefore, replaced by the first half-wave of a periodic alternating current with a vectorial angular velocity $\tau = 200$ and a frequency $f = \frac{1}{T} = 31{\cdot}3$.

Assuming the internal E.M.F. e to be constant, the electrical short-circuit power is determined as follows:

$$N_e = e\, i_1 \sin \tau t \text{ watts} = \frac{e\, i_1}{9{\cdot}81} \sin \tau t \text{ mkg per sec.}$$

The angular velocity of the armature changes only inconsiderably during the time the short circuit lasts; hence the braking torque due to the short-circuit power is

$$M_e = \frac{N_e}{\omega_0} = \frac{e\, i_1}{9{\cdot}81\, \omega_0} \sin \tau t = \mu \sin \tau t$$

$$\text{where } \mu = \frac{e\, i_1}{9{\cdot}81\, \omega_0}$$

The torque exerted by the armature in consequence of the retardation of its masses is

$$M_g = J \frac{d^2\varphi}{dt^2}$$

where J = the moment of inertia of the armature, and φ = the angular displacement of the armature.

[1] See Revue BBC, 1915, No. 12.

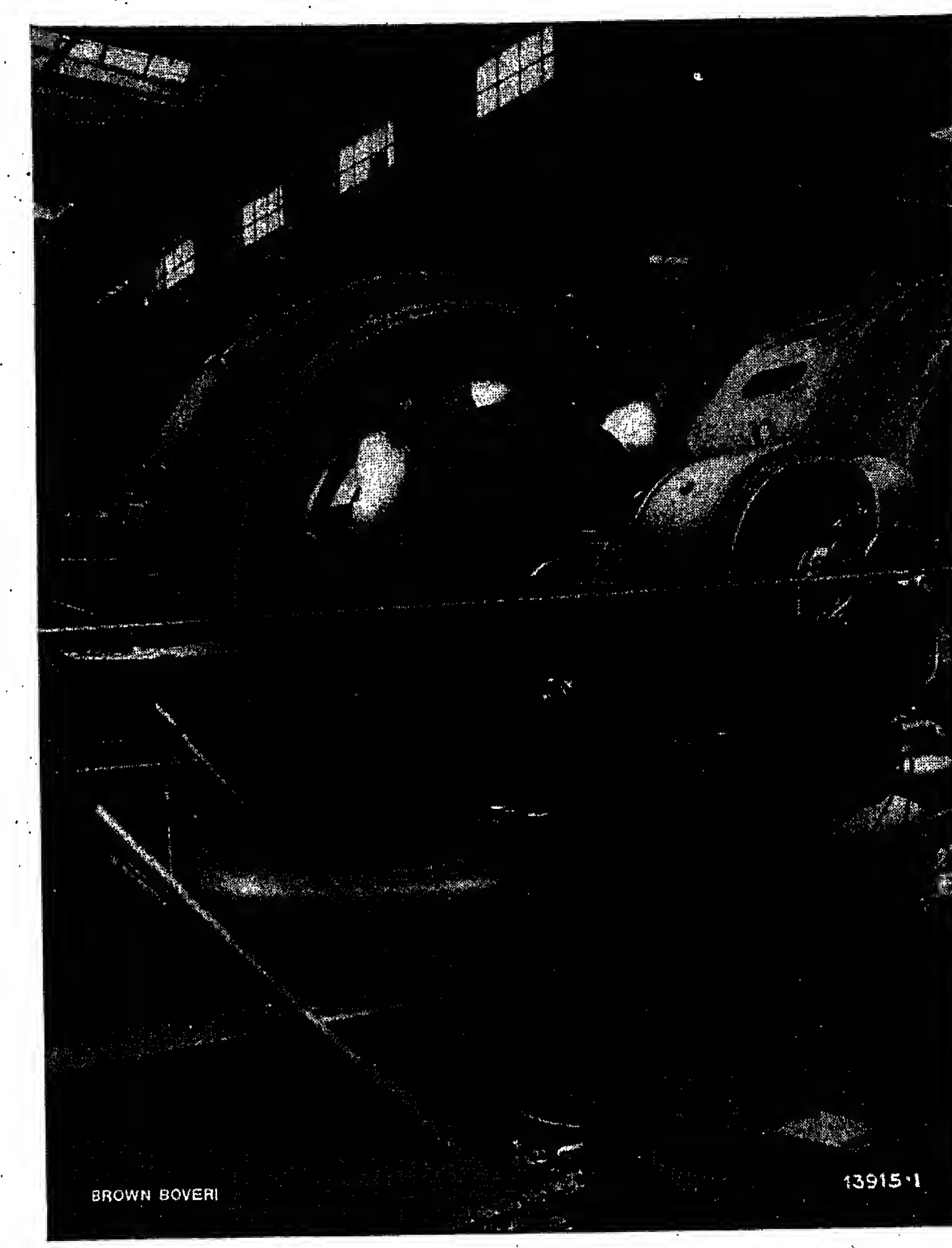


Fig. 8. — Short circuit of a rotary converter provided with Brown Boveri patent commutating poles. This is the machine on which the tests described in the text were carried out.

As the short-circuit power is covered by the generator output due to the retardation, it is possible to write

$$-M_g = M_e \text{ or } -J \frac{d^2\varphi}{dt^2} = \mu \sin \tau t.$$

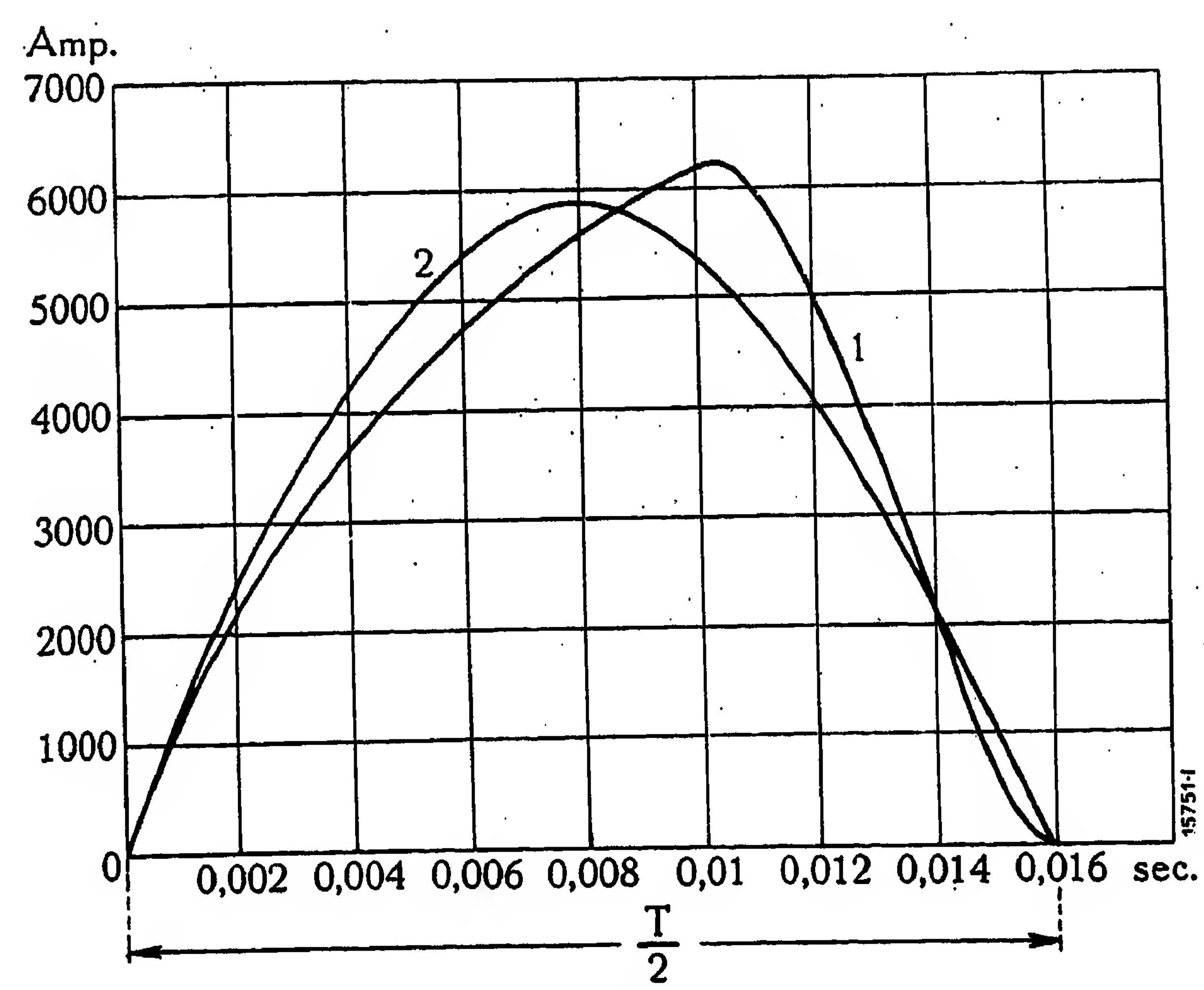


Fig. 9. — Curve of the short-circuit current.
1. Actual current. 2. Equivalent sine wave.

The solution of this differential equation is

$$\varphi = \frac{\mu}{J \cdot \tau^2} \sin \tau t + K_1 t + K_2.$$

The integration constants K_1 and K_2 are got from the limiting conditions:

$$\text{for } t = 0 \text{ and } \varphi = 0,\ K_2 = 0;$$

$$\text{for } t = 0 \text{ and } \frac{d\varphi}{dt} = \omega_o = 78{\cdot}5,$$

$$K_1 = \omega_o - \frac{\mu}{J\tau}.$$

The angular displacement

$$\varphi = \omega_o t - \left(\frac{\mu t}{J\tau} - \frac{\mu}{J\tau^2} \sin \tau t\right) = \omega_o t + \gamma,$$

the relative angular displacement

$$\gamma = - \frac{\mu}{J\tau^2} (\tau t - \sin \tau t) \text{ in radians},$$

the angular velocity

$$\omega = \frac{d\varphi}{dt} = \omega_o - \frac{\mu}{J\tau} (1 - \cos \tau t) = \omega_o + \omega',$$

the additional angular velocity

$$\omega' = - \frac{\mu}{J\tau} (1 - \cos \tau t),$$

and the angular acceleration

$$\varepsilon = \frac{d\omega}{dt} = - \frac{\mu}{J} \sin \tau t,$$

while the output of the armature is

$$N_g = M_g \cdot \omega = J\,\varepsilon\,\omega \simeq \omega_0\,\mu \sin \tau t \text{ mkg per sec.}$$

The solution of the differential equation shows that the output of the armature will be very nearly equal to the electrical short-circuit output. The reason that it is not exactly the same is explained by the fact that, when determining the latter, the fall in the E. M. F., due to the slight reduction in the speed of the armature, was neglected in order to make the differential equation simpler. The same holds good for the mechanical energy given up by the armature from the commencement of the short circuit until any instant t. Only the simple approximate formula for this need be given here; it is

$$A = \int_0^t N_g\, dt \simeq - \int_0^t N_e\, dt = \frac{\omega_o \mu}{\tau} (1 - \cos \tau t) \text{ mkg}.$$

From this equation it is possible to obtain curves showing the characteristic kinetic quantities; these are shown in Fig. 10. The curves refer to a maximum short-circuit current of about 6200 A, an E.M.F. of e = 1650 V, and a short-circuit lasting 0·016 sec.

The mean value of the current was found to be 3800 A, and the peak value of the equivalent sine-wave current 5950 A.

The curves require no special explanation. The torque due to the retardation of the masses varies proportionally, and the output roughly proportionally, to the angular acceleration ε; the work done is approximately proportional to the additional angular velocity ω'. The angular displacement increases at first only slowly, but towards the end of the short-circuit period it increases rapidly. In consequence of the maximum slip attained when the circuit is interrupted, it still increases steadily thereafter.

The asynchronous torque M_a and the synchronous torque M_s are shown to a large scale in Fig. 11. The first of these varies proportionally with the slip, and the second with the angular displacement γ, or with sin p γ. In Fig. 10 the asyn-

Fig. 10. — Displacement of the armature during the short-circuit period.
1. Generating torque (left-hand ordinates). Angular acceleration (right-hand ordinates).
2. Generating torque for actual change in current.
3. Asynchronous torque.
4. Additional angular velocity.
5. Angular displacement.
6. Output as a generator.
7. Output as a generator for actual change in current.
8. Work as a generator.

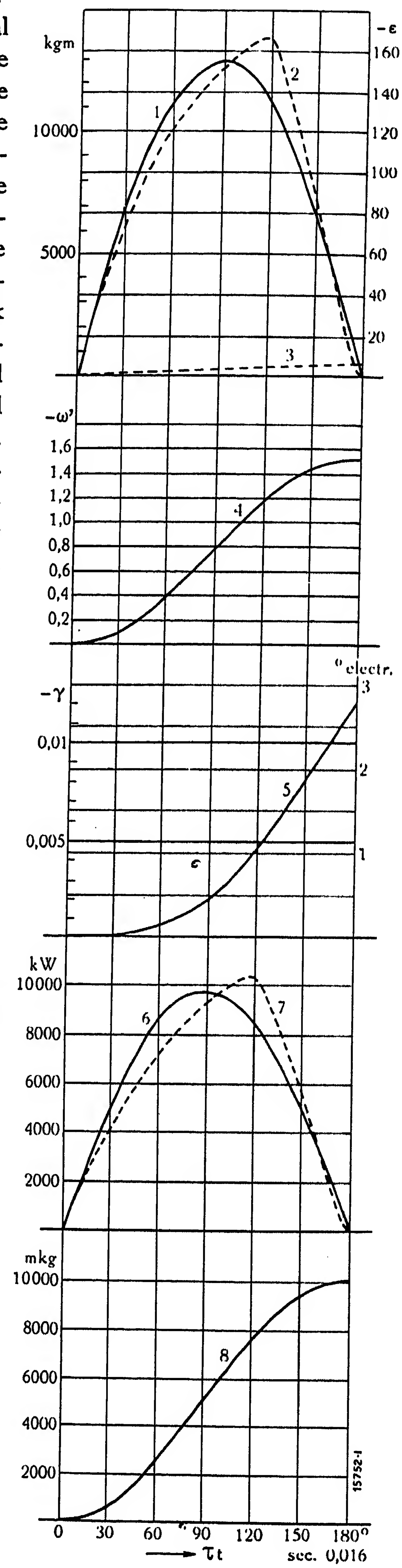


Fig. 10.

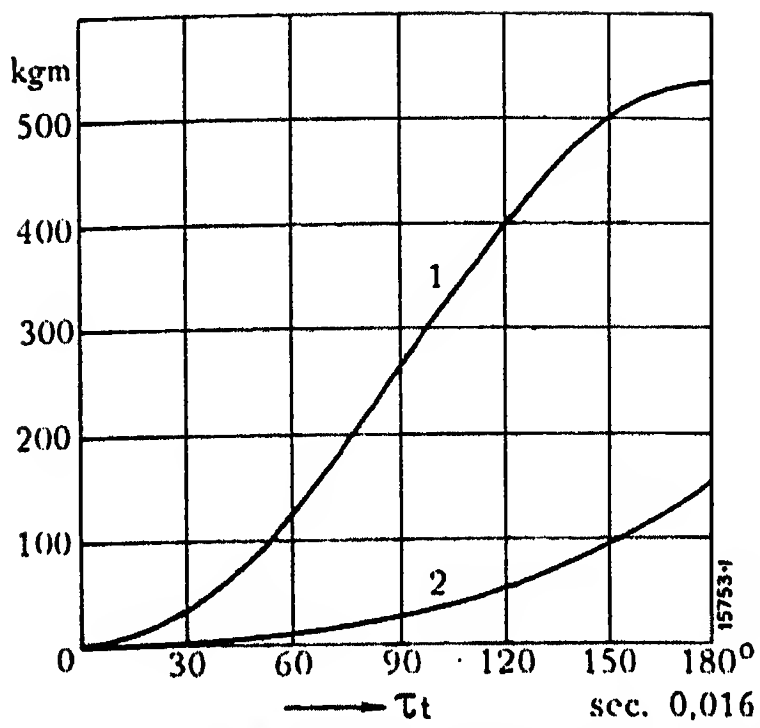


Fig. 11. Electrical torques during the short-circuit period.

1. Asynchronous torque. 2. Synchronous torque.

chronous torque is also indicated by the dotted curve to the scale of the kinetic torque, and its value can there be compared directly with the latter. It is clear, therefore, that the effect of the electrical torques can reduce the kinetic energy given up by only an insignificant amount and that the shape of the calculated curves would, in consequence, be only slightly altered.

In reality, a further discrepancy has to be reckoned with, due to the fact that the short-circuit current is not a real sine wave, as assumed for simplifying the mathematical treatment. Since the generating torque is nearly proportional to the short-circuit current, it would be indicated in Fig. 10 by a curve of the same shape as that of the current 1 (Fig. 9) instead of by a sine wave. The power curve in Fig. 10 would be displaced in exactly the same manner, the correct output curve being obtained by graphical integration. Similarly the additional angular velocity $-\omega'$, and from it the angular displacement $-\gamma$, could be got from the acceleration $-\varepsilon$. They would be somewhat lower than the calculated curves at the commencement, and somewhat steeper towards the end.

VIII. THE MAGNETIC FLUCTUATIONS.

For the sake of simplicity, the magnetic fluctuations in the rotary converter during the short circuit have not yet been taken into consideration; it is now desirable, however, to refer to them briefly, in so far as they have a bearing on the output of the machine when operating as a generator.

The *armature reaction* of the short-circuit current results in a tendency for a strong cross field to be set up. This is effectively damped, however, by the ample amortisseur winding, which acts towards maintaining the disposition of the field unaltered. The currents in the amortisseur winding, and the increasing of the current in the shunt winding, similarly act to oppose any important change in the strength of the main field. Further, a reduction of the latter is followed by magnetising currents being drawn from the alternating-current mains, this effect being stronger the more constant the pressure remains at the alternating-current terminals. The assumption made—that the E. M. F. on the direct-current side of the converter would remain approximately constant—does not therefore seem to be inadmissible.

By reason of the short-circuit current, strong leakage fields are, in addition, produced in the armature, and in a lesser degree round the other conducting parts of the circuit carrying the current. The amount of energy stored in these fields at the instant the short-circuit current reaches its maximum value represents a considerable amount of work, which, however, disappears again when the circuit is interrupted.

To calculate the leakage voltage, the coefficient of self-induction L of the circuit must be known; it amounts to about 1·5 mH. The energy stored with the peak value of the short-circuit current $i = 6000$ A, is

$$A' = \frac{Li^2}{2} = \frac{0{\cdot}0015 \times 6000^2}{2} \text{Wsec} = 27 \text{kWsec} = 2750 \text{mkg}.$$

If, for the sake of simplicity, the short-circuit current is again considered as a half of a sinusoidal current wave, the above energy is all stored in the stray fields 0·008 sec after the short circuit occurs, and after a further 0·008 sec it has again disappeared, according to the equation $A = \frac{Li^2}{2} \sin^2 \tau t$ (Fig. 12).

The *power* corresponding to this amount of energy follows a sine wave of double frequency:

$$N = \tau \frac{Li^2}{2} \sin 2\tau t.$$

The maximum values of the power are found to be

$N = +5400$ kW at time $t = 0{\cdot}004$ sec.

$N = -5400$ kW „ „ $t = 0{\cdot}012$ sec.

A very considerable exchange of energy is therefore necessitated by the stray fields. The question now is: From what source of energy will these variations be compensated?

In consequence of the leakage fields, the short-circuit current flowing through the armature from one set of brushes to another generates an E. M. F. of self-induction, which disturbs the balance between the terminal pressure on the alternating-current side and the induced back E. M. F. of the

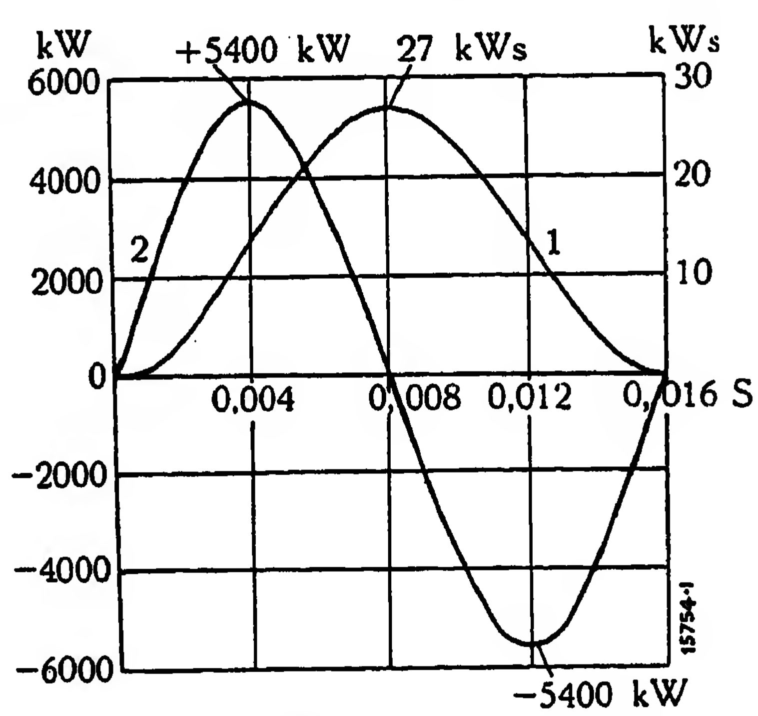


Fig. 12. — Magnetic equalisation.

1. Energy. 2. Power.

armature. Due to this difference in pressure, a current flows into the machine from the mains, and it assumes a value that varies as the leakage pressure of the short-circuit current, this latter pressure being, for its part, dependent on the value of the short-circuit current itself. The current taken from the alternating-current mains will be different in the three phases. Besides being dependent on the instantaneous value of the short-circuit current, it varies also with the instantaneous position of the primary phase connection relative to the direct-current brushes. The integration of the products of these alternating currents and their phase pressures represents a power which is the equivalent of that flowing in the leakage fields. It is zero at the moment the short-circuit current reaches its peak value, and from that instant becomes negative; that is, the energy of the leakage fields flows back again to the supply system. As regards the flow of energy, this process much resembles the ordinary phenomena of an inductive load on an alternating-current system. The above considerations lead to the conclusion that the kinetic conditions in the armature, namely the generator effect during the short circuit, will not be influenced by the exchange of energy in the leakage fields.

In the present article it is not proposed to deal with the *hunting of the armature after switching off*, nor with the conditions to be fulfilled with regard to the length of time for interrupting the circuit, and the values of the synchronous and the asynchronous torques necessary to prevent the converter falling out of step. Such questions will probably be dealt with at a future date.

(MS 271) *F. Hœberli. (J. F. L.)*

THE TRANSPORT OF A 13'000-kVA TRANSFORMER SUPPLIED TO THE SWISS POWER TRANSMISSION CO., BERNE.

Decimal index 656:621. 314. 3.

THE Amsteg power station of the Swiss Federal Railways contains, in addition to four single-phase generators of 9000 kW each, a three-phase generator of 9100 kW, 0·7 power factor, 8600 V, 50 cycles, 300 r. p. m.[1] This machine is provided so that the surplus energy of the power station can be utilised for industrial purposes. With this object, the Swiss Power Transmission Co., Berne, have installed an outdoor transformer station (Fig. 1) near the central station. The equipment of this station includes a three-phase transformer of 13'000 kVA, 8600/79'000 V, 50 cycles, with forced oil cooling, and a switchboard carrying the necessary 8600-V instruments and apparatus.

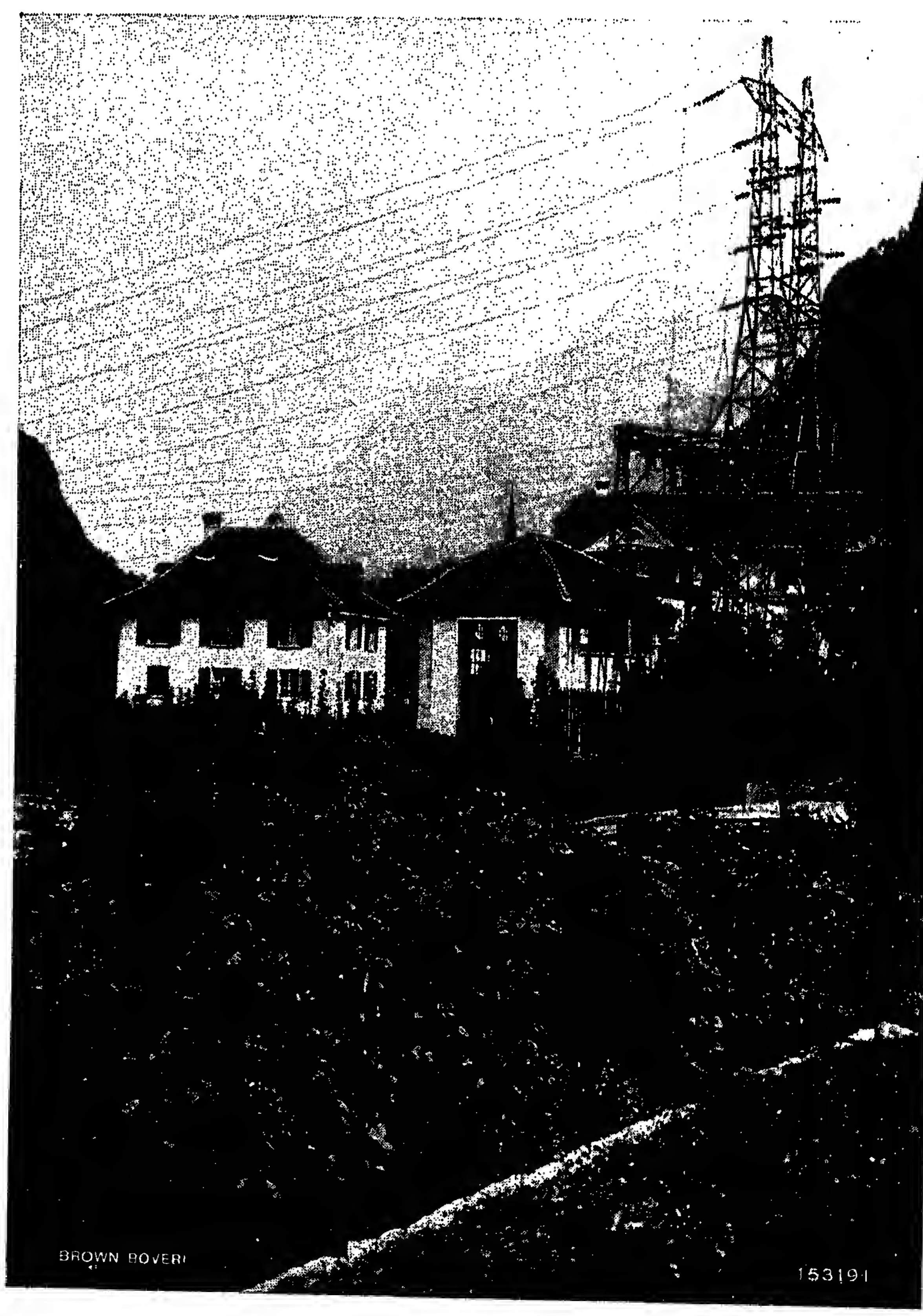


Fig. 1. — General view of the outdoor substation and high-tension transmission tower.

The 80'000-V apparatus is situated outside the substation and consists of three single-pole oil circuit breakers with electric remote control, choke coils, and disconnecting switches. This is the starting point of the 80'000-V three-phase distribution system for industrial power, as well as of four 60'000-V single-phase lines for the Swiss Federal Railways. The energy is transmitted at 8600 V from the central station to the transformer through two cables in parallel, each 3×120 mm² in cross-section. In the central station itself, three single-pole oil circuit breakers with motor remote control are installed in armoured cells, and, on a switch desk in the control room, the instruments for measuring the electric energy delivered by the three-phase generator are mounted. These instru-

[1] See The Brown Boveri Review, 1923, No. 8, p. 154.

ments are connected to current and pressure transformers.

The fitting up of this plant, the conveying of the various parts, and their erection naturally involved a considerable amount of preparatory work. The following account deals briefly with the transport of the 13'000-kVA transformer.

Having regard to the conditions at Amsteg, the transformer was dispatched from the Brown Boveri workshops ready for service, with the exception of the fact that the oil was drained from the tank. This measure was necessary to reduce the weight to be handled to 25 tons, which was the maximum capacity of the lifting gear and conveyance available, and also of the bridge over the Kerstelenbach which had to be crossed.

For the railway journey between Baden and Amsteg, Brown, Boveri & Co. employed one of their six-axle crocodile trucks upon which the transformer and its tank were loaded, together with the oil for filling the latter, the accessories, and the necessary supports and lifting tackle. At Amsteg railway station the transference of the transformer from the truck to a special trolley belonging to the Bernese Power Supply Co., Berne, was effected by a 25-ton crane (Fig. 2).

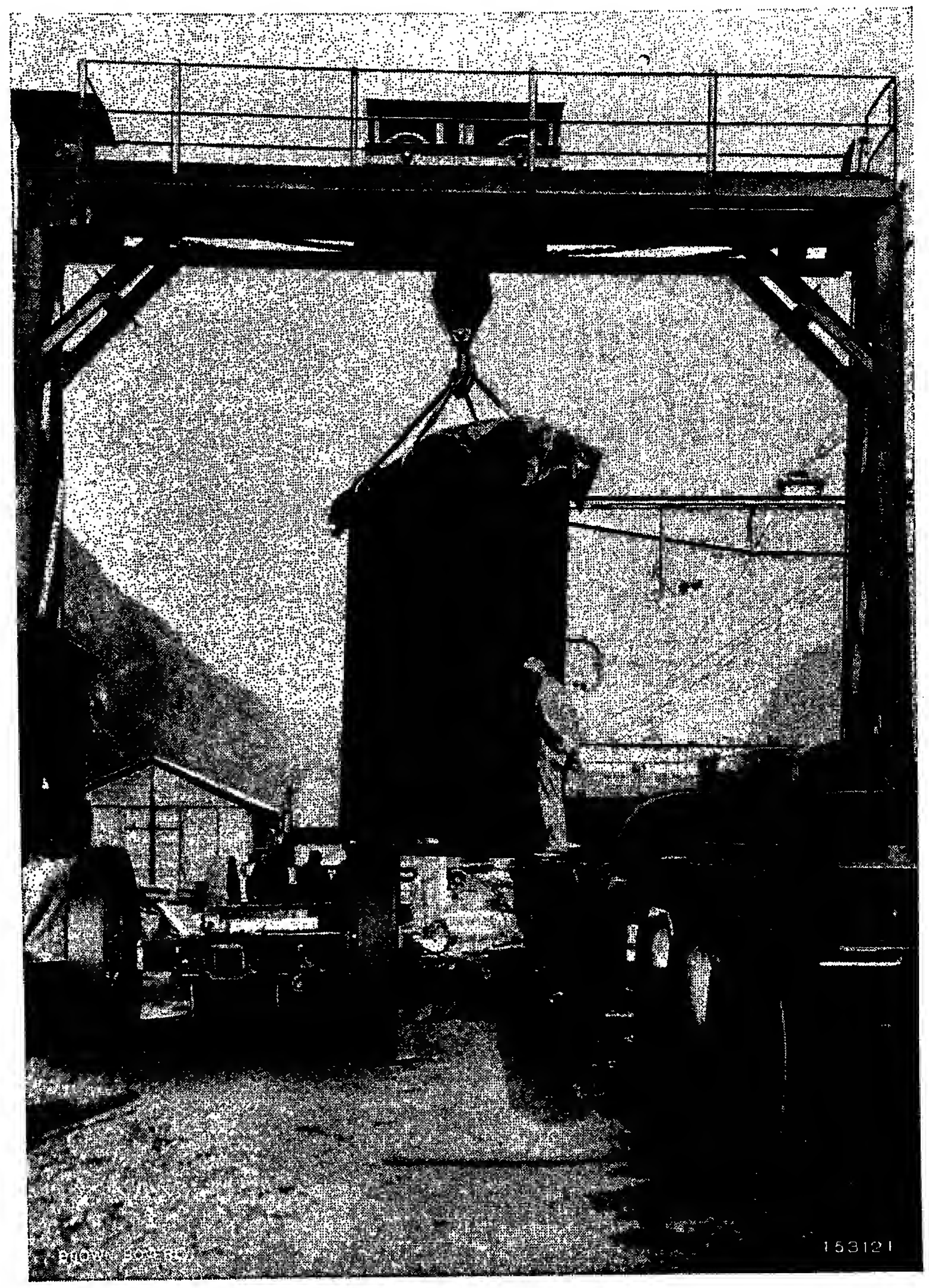


Fig. 2. — Transferring the 25-ton transformer from the railway truck to the lorry at Amsteg railway station.

This trolley, which is constructed entirely of steel, has a large loading platform and very effective brakes, both pairs of wheels being capable of swivelling. Together with its load, it weighed 33 tons and was hauled from the railway to the power station by a forty-horse-power tractor (Fig. 3), which was supplied by Messrs. Welti-Furrer, transport contractors, Zurich. The journey was accomplished without any mishap, and unloading was carried out with the aid of the crane at the central station. After its wheels had been fitted, the transformer was placed upon lengths of channel iron and flat strip as shown in Fig. 4, and in this way was moved into position, about 150 m from the central station. Fig. 5 shows the transformer just after reaching the specially prepared incline on which sleepers and rails had been laid. This incline, which is 20 m long and has a gradient of 6 %,

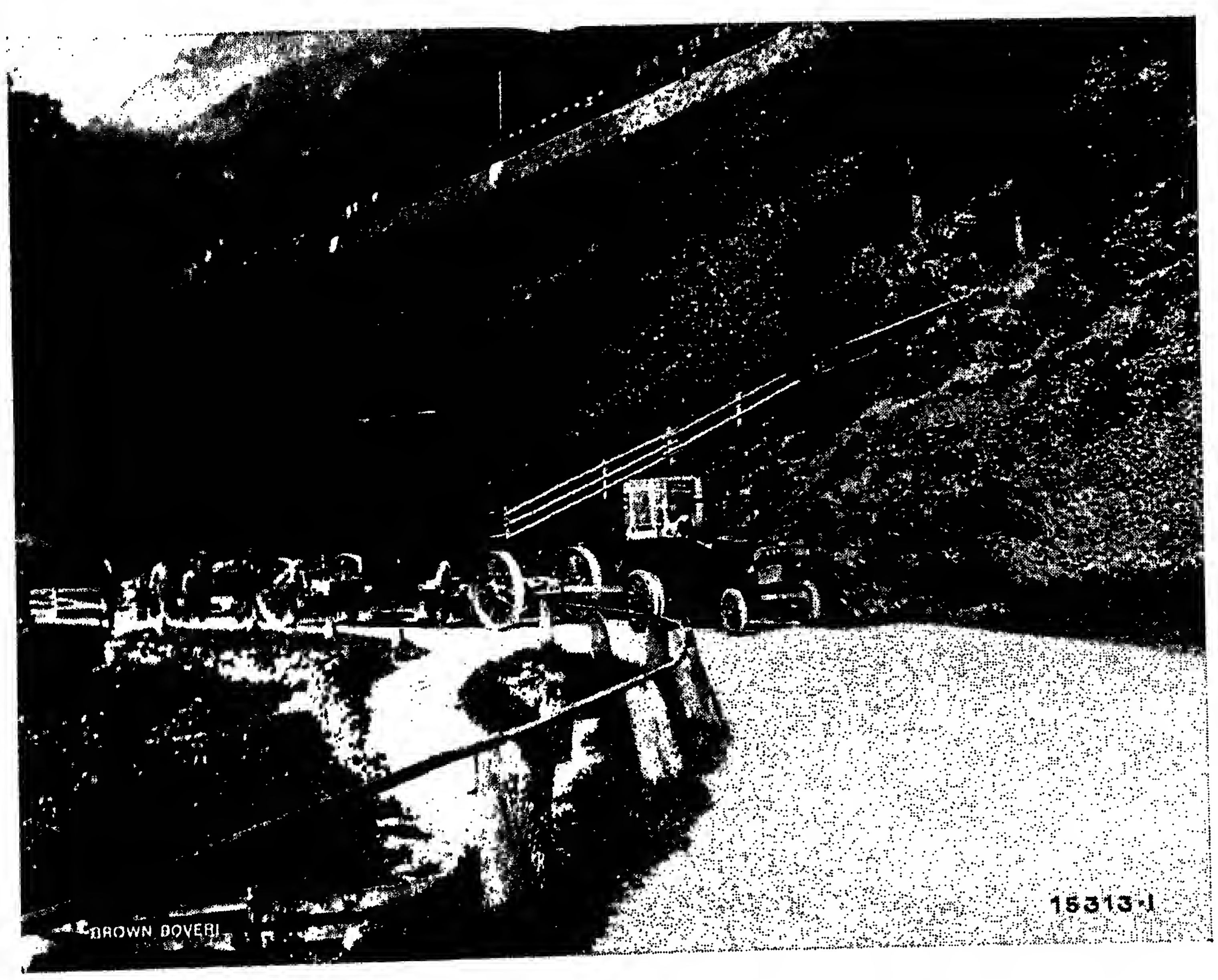


Fig. 3. — Transformer on the road from the railway to the central station.

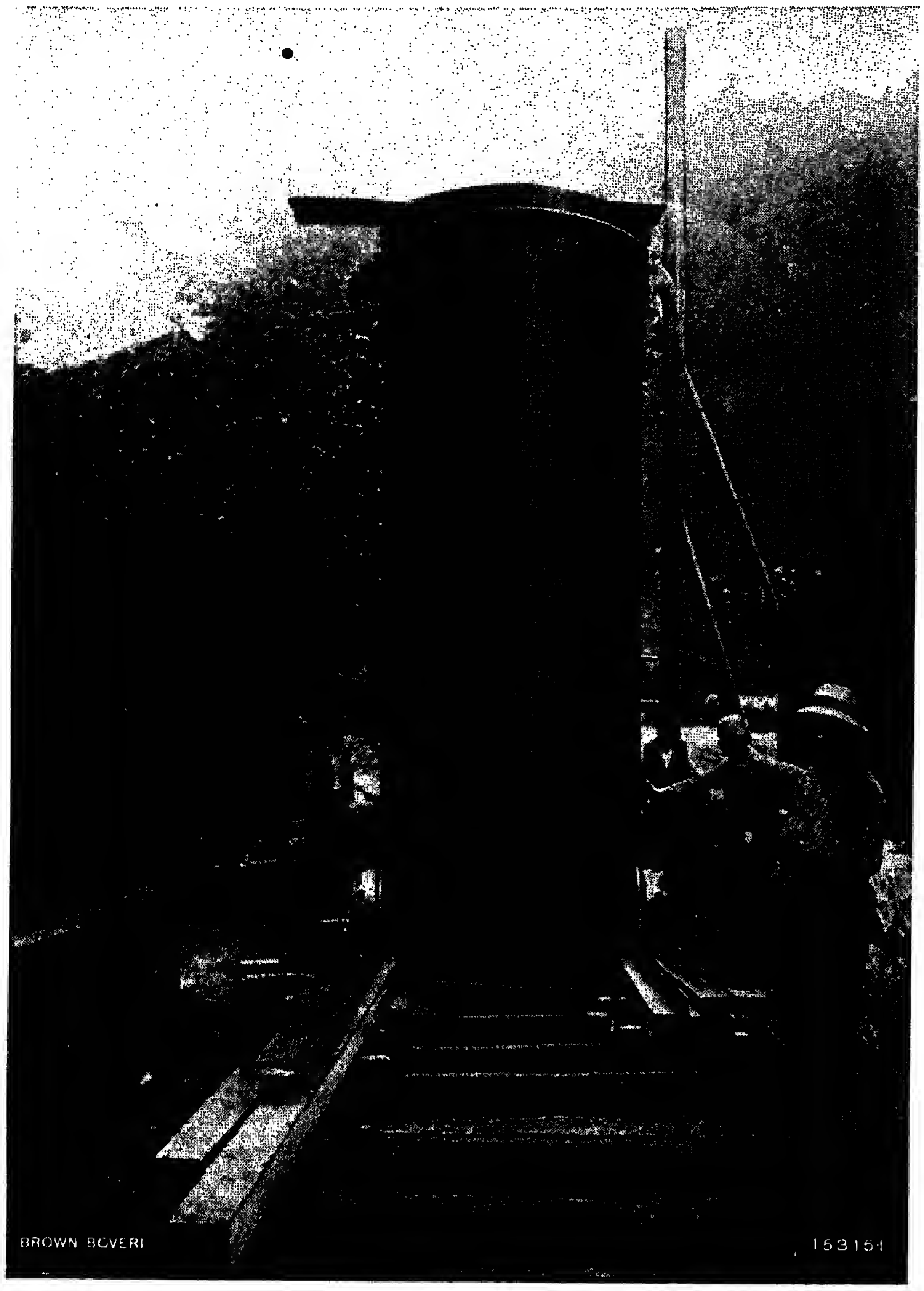


Fig. 4. — Transformer being moved on the last part of its journey on its own wheels.

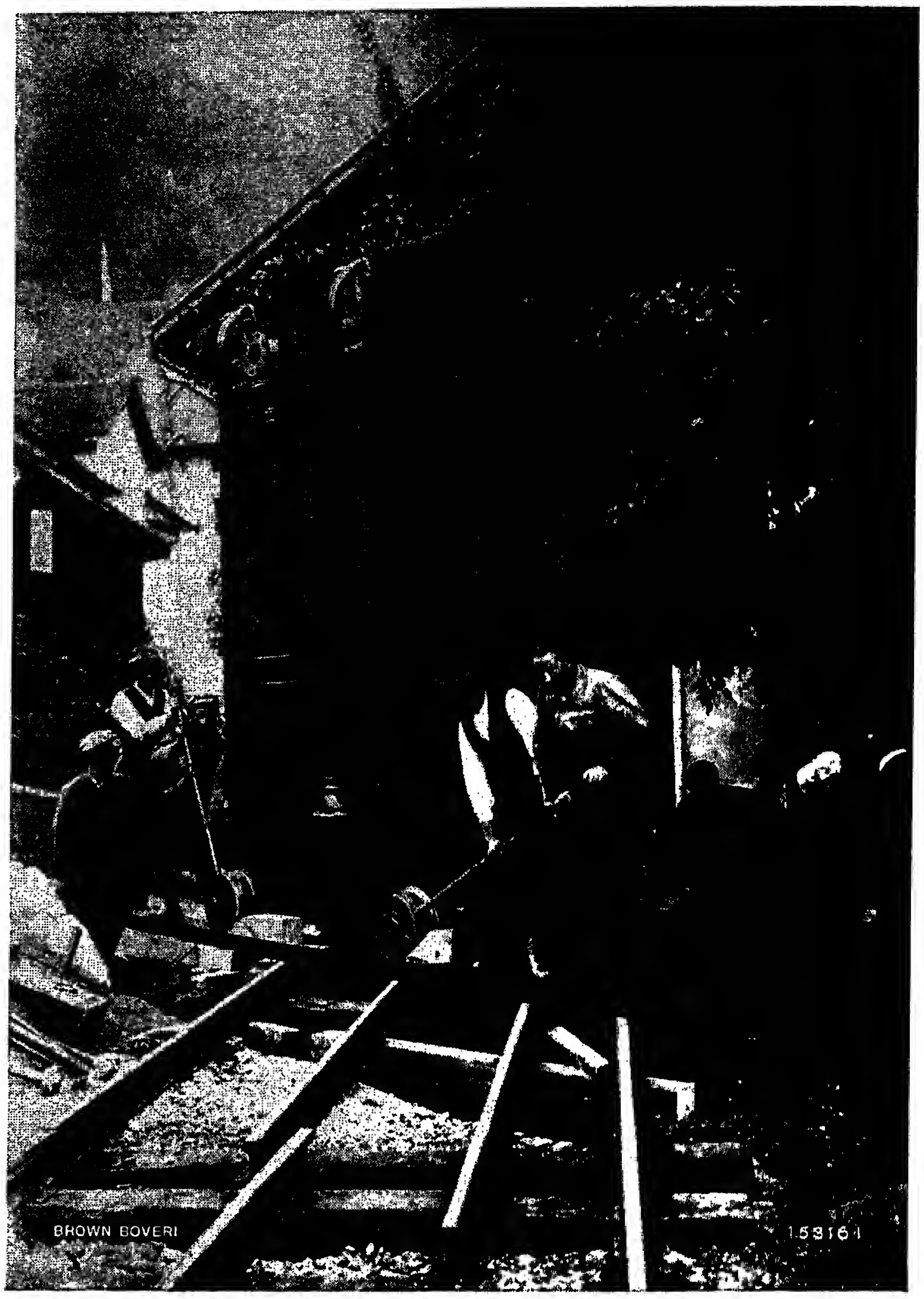


Fig. 5. — Transformer at the beginning of the incline; channel irons were placed beneath the wheels.

has been allowed to remain intact for future use. It was so arranged that, on reaching the entrance to the sub-station, the transformer could be wheeled into position upon the permanent track provided for the purpose.

Fig. 6 shows the transformer, and the channel irons on which it rests, being pulled up the slope with the help of a powerful block and tackle, preparatory to being placed in position.

After three days' work, all obstacles had been safely overcome, the tank was refilled with oil and the transformer made ready for service.

(MS 267) O. Steiger.
(G. T. S.)

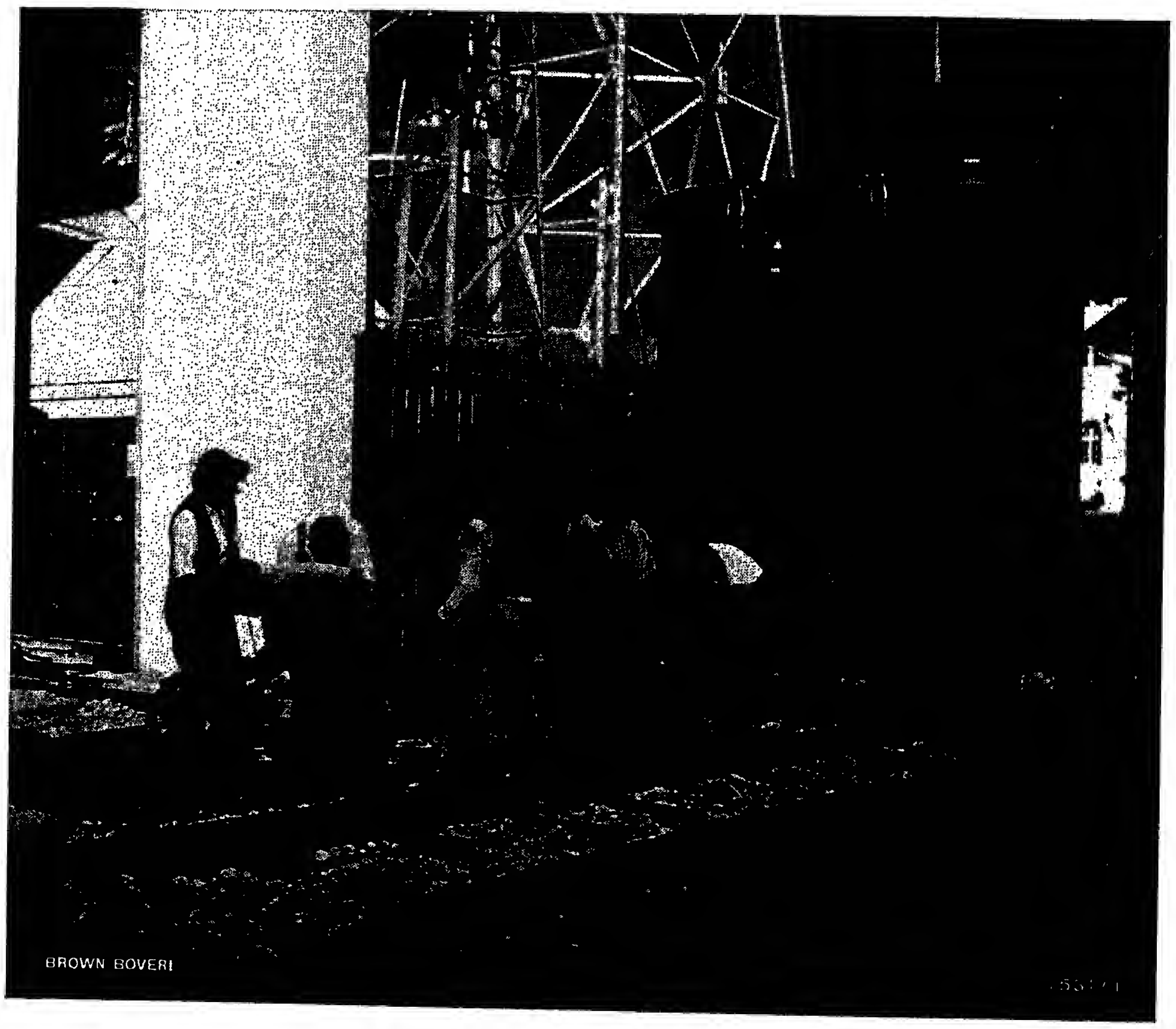


Fig. 6. — Transformer being moved up the incline with the help of a block and tackle.

THE CURRENT CONDITIONS IN TRANSFORMERS WORKING ON UNBALANCED LOAD.

Decimal index 621. 308 : 621. 314. 3.

In practice, the idea is very prevalent that unbalanced loading of the secondary of a three-phase transformer may be compensated on the primary side if the windings are suitably connected. Technical literature throws very little light on this subject, and it is the purpose of the present article to investigate more fully the current conditions prevailing in a transformer loaded in this manner.

It is usual and, as shown further on, essential to connect transformers in delta-star, star-zigzag, or delta-zigzag when they are subjected to unbalanced loading, such as lighting load or mixed load (both motors and lighting). As a rule, the neutral point of these transformers is brought out so that the lighting load can be applied between the neutral wire and the individual phases, while motors can be connected to the three-phase system. When transformers are provided to feed lighting mains only, the load can also be distributed between the three phases.

Throughout this article the following symbols are employed:

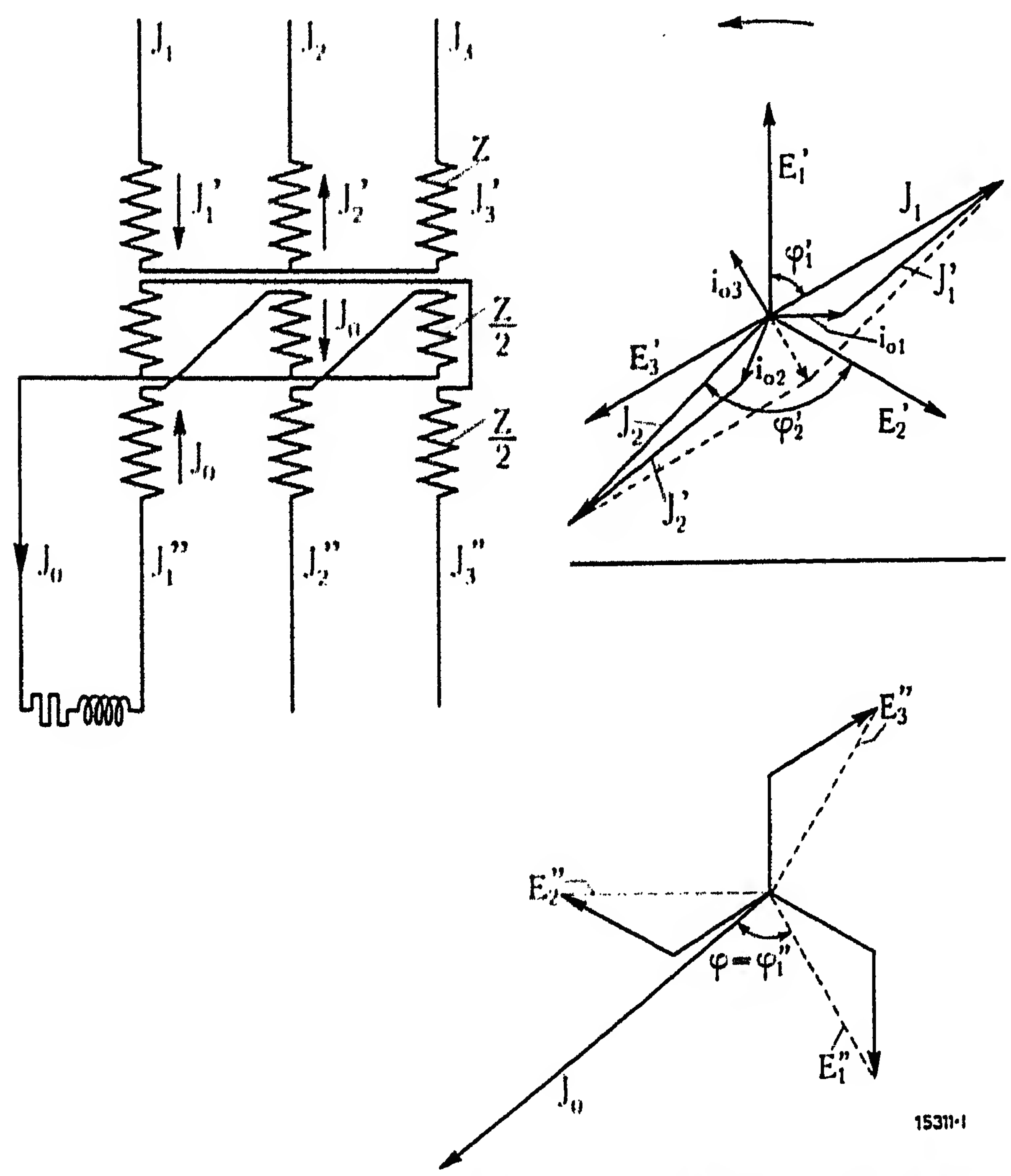


Fig. 1. — Diagram of connections and vector diagrams of a star-zigzag transformer with a single-phase load applied between the neutral point and one phase.

E_1' = primary terminal pressure in phase 1
E_2' = " " " " " 2
E_3' = " " " " " 3
E_1'' = secondary " " " " 1
E_2'' = " " " " " 2
E_3'' = " " " " " 3
J_1' = primary load current in phase 1
J_2' = " " " " " 2
J_3' = " " " " " 3
J_1'' = secondary current in phase 1
J_2'' = " " " " 2
J_3'' = " " " " 3

i_{01}, i_{02} and i_{03} = no-load currents in the corresponding phases.

J_0 = load current.

φ_1', φ_2', φ_3' = phase displacements between the primary pressures and currents in the three phases.

φ_1'', φ_2'', φ_3'' = phase displacements between the secondary pressures and currents in the three phases.

φ = phase displacement between the terminal pressure and the load current.

J_1 = primary line current in phase 1
J_2 = " " " " " 2
J_3 = " " " " " 3

I. TRANSFORMERS WITH STAR-ZIGZAG CONNECTION.

(a) In spite of all the efforts which have been made in practice to load the individual phases of transformers as equally as possible, exact uniformity cannot be obtained, particularly on lighting systems. By chance, or as a result of some disturbance, it is even possible for the extreme state of unbalance to occur, i.e., the loading of a single phase only.

Suppose a transformer connected as in Fig. 1 to be loaded between the neutral wire and phase 1, then:

$$J_1'' = J_0 \text{ and } J_2'' = J_3'' = 0.$$

The vector sum of the ampere-turns for the magnetic circuits of a three-phase transformer, as represented by I, II, and III in Fig. 2, must be zero. Hence, assuming throughout an equal number of turns on both primary and secondary ($z_1 = z_2 = z$), the currents are given by the following equations. In general, these only hold good vectorially, but in the present case they are arithmetically correct also:

$$(1) \quad J_0 \cdot \frac{z}{2} - J_1' \cdot z + J_0 \cdot \frac{z}{2} - J_2' \cdot z = 0$$

$$(2) \quad - J_0 \cdot \frac{z}{2} + J_2' \cdot z - J_3' \cdot z = 0$$

$$(3) \quad J_0 \cdot \frac{z}{2} - J_1' \cdot z - J_3' \cdot z = 0$$

From these three equations, the three unknown primary currents can be derived:

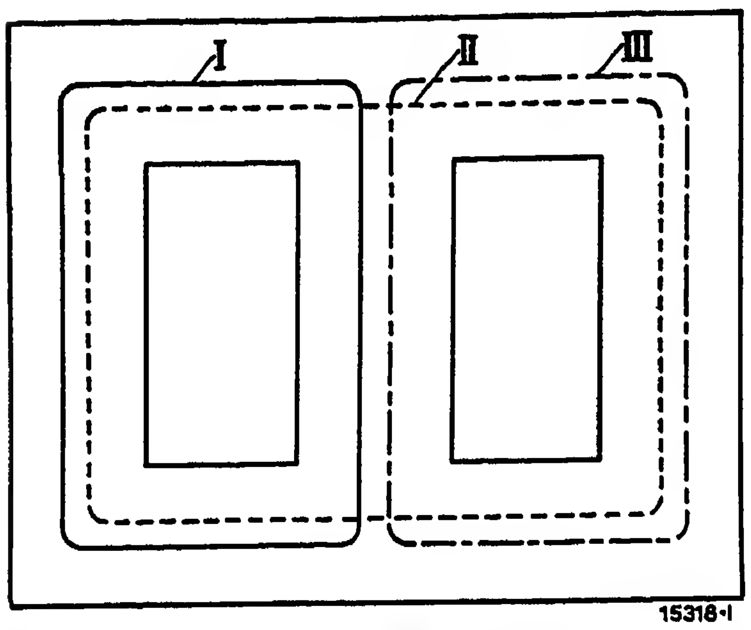


Fig. 2. — Iron core of a three-phase transformer with the magnetic circuits I, II, and III.

$$J_1' = J_2' = \frac{J_0}{2}$$

$$J_3' = 0.$$

The directions of flow of the primary and secondary currents are indicated by the arrows in Fig. 1.

The secondary current is supposed to be lagging by an angle φ which is equal to φ_1'' given in the vector diagram (Fig. 1). A single-phase load on the secondary side is essentially transmitted as such to the primary.

The primary line currents, i. e., the currents taken from the mains, are found by geometrical addition of the load currents in the individual phases to the no-load currents, as shown in the vector diagram of Fig. 1, in which the primary currents are set out according to their direction and to the values obtained from the equations.

This construction may be verified by Kirchoff's law, according to which the vector sum of all currents flowing to and from the neutral point must be zero ($J_1 + J_2 + i_{03} = 0$).

For the sake of simplicity, no account is taken of the small watt components of the no-load currents due to the iron losses.

Thus, apart from the magnetising current, a single-phase secondary load results in the equal loading of two phases of the primary but with different phase displacements.

As can be seen from the diagram, an entirely non-inductive secondary load gives rise to considerable phase displacement in the primary circuit.

(b) If current is taken from two secondary phases of a transformer connected in star-zigzag, this being the alternative method of applying a single-phase load, the following relations hold:

$$J_1'' = J_2'' = J_0 \text{ and } J_3'' = 0.$$

The currents flow as indicated by the arrows in Fig. 3. Considering the fact that the vector sum of the ampere-turns of the magnetic circuits shown in Fig. 2 must be equal to zero, the load currents in the primary phases may be obtained from the following equations: (The number of turns composing the windings are here neglected, as they would be eliminated in the subsequent calculations.)

$$(1) \quad \frac{J_0}{2} - J_1' + \frac{J_0}{2} - J_2' + \frac{J_0}{2} = 0$$

$$\text{or } \frac{3}{2} J_0 - J_1' - J_2' = 0$$

$$(2) \quad \frac{J_0}{2} - J_1' - \frac{J_0}{2} + J_3' = 0$$

$$\text{or } J_1' = J_3'$$

$$(3) \quad - \frac{J_0}{2} - \frac{J_0}{2} + J_2' - \frac{J_0}{2} + J_3' = 0$$

$$\text{or } - \frac{3}{2} J_0 + J_2' + J_3' = 0$$

$$(4) \quad J_1' + J_2' + J_3' = 0$$

From these three equations, it follows that:

$$J_1' = J_3' = \frac{J_0}{2}$$

$$J_2' = J_0$$

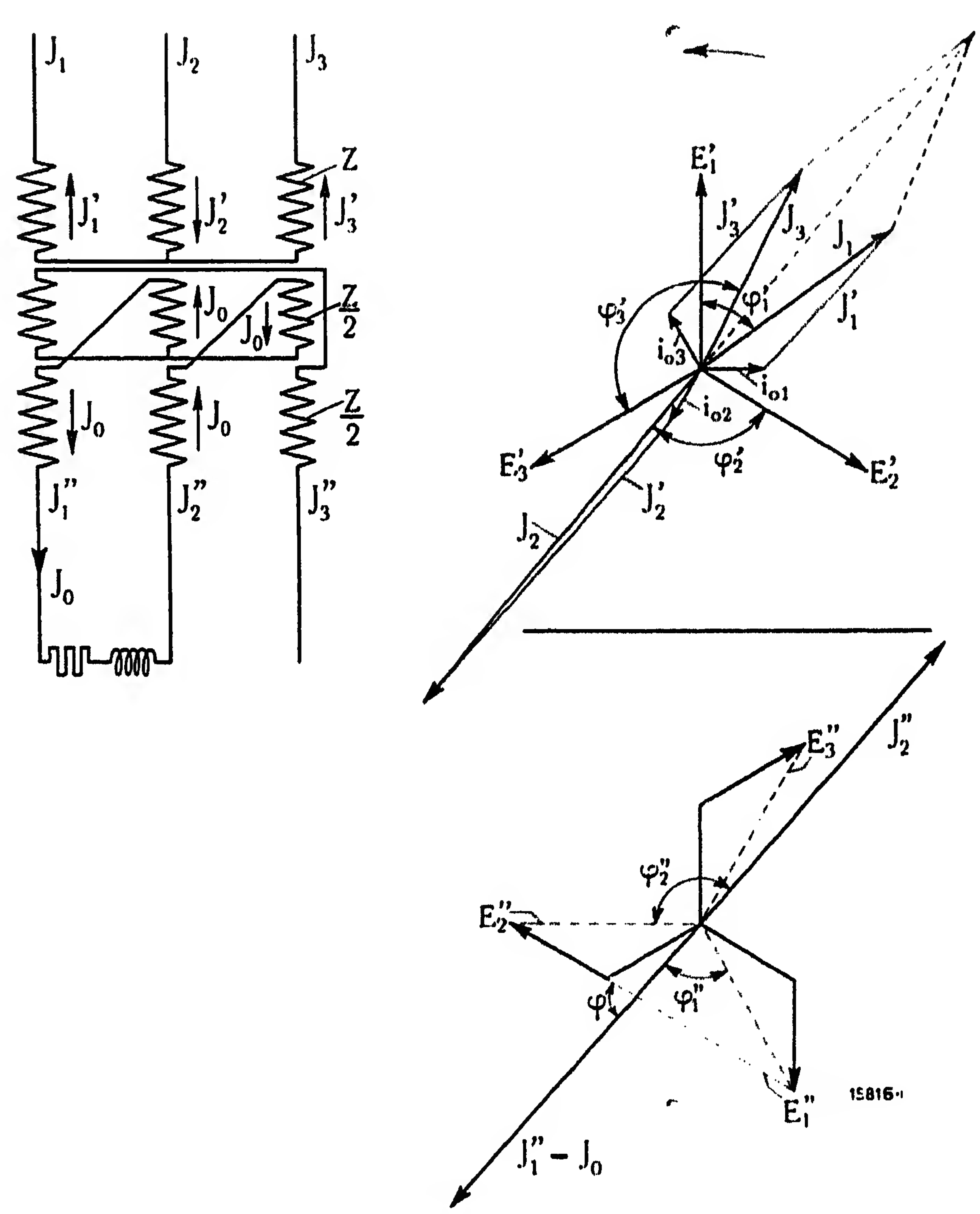


Fig. 3. — Diagram of connections and vector diagrams of a star-zigzag transformer with a single-phase load applied between two phases.

These primary load currents combined with the magnetising currents of the corresponding phases give the line currents J_1, J_2 and J_3, of which the vector sum is again zero, as seen from the diagram in Fig. 3. This diagram also shows that, notwithstanding the fact that a load current flows in all three conductors, the loading of the system is not uniform, as, apart from the magnetising current, two of the phases carry half the current flowing in the third, while the phase displacement is different for all three phases.

(c) If the loading of a transformer connected in star-zigzag includes motors (three-phase) as well as lamps (single-phase), the load may always be regarded as being composed of two portions — a perfectly balanced three-phase load, and a single-phase load applied either between one phase and neutral, or between two of the phases. The currents flowing in the three primary mains can be readily determined by superposing the currents resulting from the single-phase load, whether corresponding to case a or b, upon those due to the balanced load.

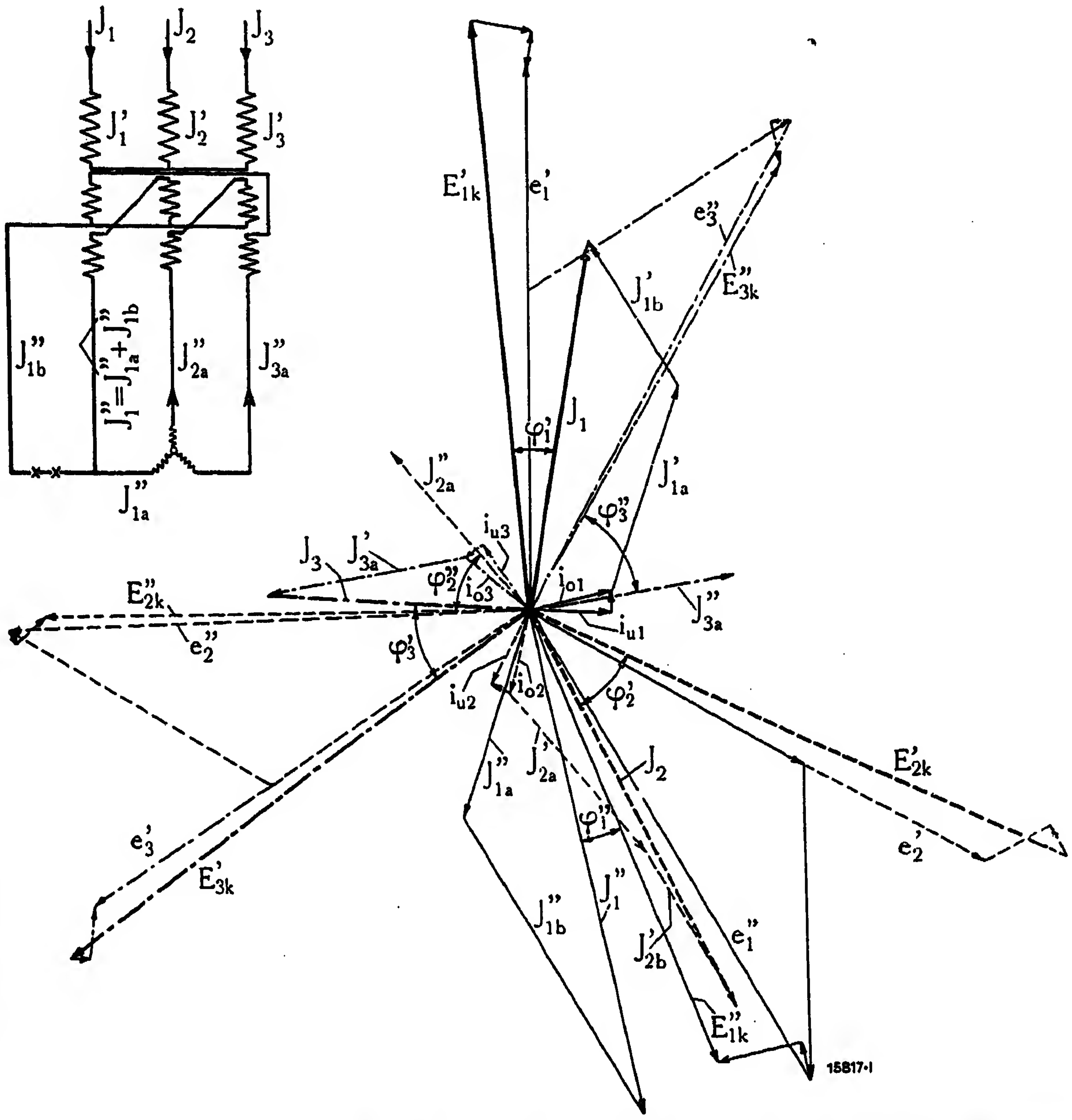


Fig. 4. — Diagram of connections and vector diagram of a star-zigzag transformer with unbalanced secondary load.

A diagram is given in Fig. 4, by which the currents and pressures can be accurately determined in a case such as outlined above. J_{1a}'', J_{2a}'' and J_{3a}'' are the balanced currents due to the three-phase load, and upon these, the single-phase load J_{1b}'' is superposed, so that, in phase 1, the total current J_1'' flows. The primary terminal pressure is assumed to be symmetrical, the terminal pressures in the three phases being E_{1k}', E_{2k}' and E_{3k}'. Since the pressure drops are different in each phase, the electromotive forces, e_1', e_2' and e_3' as well as e_1'', e_2'' and e_3'' no longer form equilaterial triangles, as a consequence of which the secondary terminal pressures E_{1k}'', E_{2k}'' and E_{3k}'' naturally become unbalanced also. The magnetising currents i_{u1}, i_{u2} and i_{u3} are at right angles to the corresponding electromotive forces and, with the watt current necessary to cover the iron losses, they constitute the no-load currents i_{01}, i_{02} and i_{03}. The balanced three-phase load is transmitted as such to the primary side with the currents J_{1a}', J_{2a}' and J_{3a}' which are geometrically added to the no-load currents. In case a, the single-phase load J_{1b}'' is transmitted to phases 1 and 2 of the primary side as two equal currents $\frac{J_{1b}''}{2}$, so that with star connection, the primary phase currents J_1', J_2' and J_3' are equal to the line currents.

Thus, an unbalanced load on the secondary of a transformer causes unbalanced loading of the primary also, resulting in different line currents and different displacements φ_1', φ_2', φ_3' on the various phases.

II. TRANSFORMERS WITH DELTA-STAR CONNECTION.

This method of connection also permits of a single-phase load being applied either between one phase and the neutral point, or between two of the phases. From the point of view of the distribution of the current with a single-phase load, it is equivalent to star-zigzag connection.

Fig. 5 illustrates the case when the load is applied between one phase and the neutral point of a delta-star transformer, E_{1k}', E_{2k}' and E_{3k}' indicating the three applied terminal pressures. As current flows in

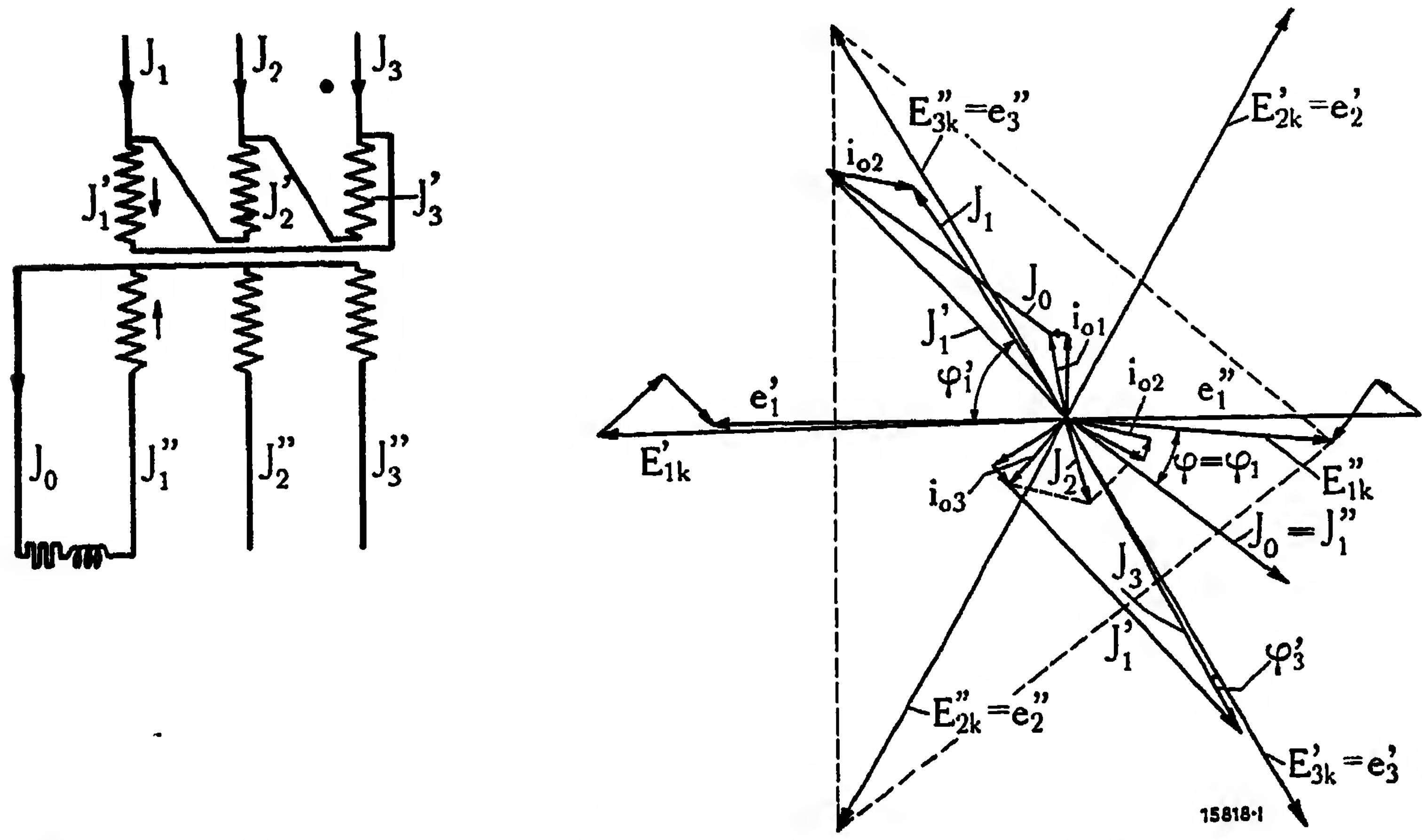


Fig. 5. — Diagram of connections and vector diagram of a delta-star transformer with a single-phase load applied between the neutral point and one phase.

one phase of the transformer, there is a pressure drop in that phase only, resulting in uneven loading of the secondary. The phase-1 line current J_1' is the resultant of the load current $-J_0$ and the magnetising currents i_{01} and i_{02}, the phase-2 current J_2' is the resultant of i_{02} and i_{03}, and the phase-3 current J_3' of $-J_1'$ and i_{03}. This can be seen from the diagram of connections, and was taken into consideration when the vector diagram was drawn.

Fig. 6 shows the effect of applying a single-phase load between two phases, which results in the secondary currents J_1'' and J_2''. In this construction, the no-load currents and pressure drops are neglected. Applying the same methods as in the cases already dealt with, the line currents J_1, J_2 and J_3 are found. As the currents J_1 and J_2 only flow in two phases of the transformer, the secondary pressures are naturally out of balance.

III. TRANSFORMERS WITH DELTA-ZIGZAG CONNECTION.

This method of connection is of particular interest, as any single-phase load, whether connected between the neutral point and one phase, or between two phases of the secondary, gives rise to a current in all three phases of the primary. This does not mean, of course, that a solution has been found to the constantly recurring problem of transforming three-phase current to single-phase. The loading on the primary side remains essentially single-phase in character, the three phase displacements being different. Thus, neglecting the magnetising current, the line currents due to a load J_0 between one phase of the secondary and the neutral are as follows:

$$J_1 = J_0 \text{ and } J_2 = J_3 = \frac{J_0}{2}$$

IV. TRANSFORMERS WITH STAR-STAR CONNECTION.

It has been shown in the foregoing that a transformer connected in ⅄/⅄, △/⅄, or △/⅄ can be loaded on a single phase up to the full output of one phase winding, without involving particular disadvantages such as magnetic leakage, pressure drop, or exchange currents.

A transformer connected in star-star will now be considered, the secondary of which is loaded between one phase and the neutral point. Applying Kirchoff's law and the laws of the magnetic circuit (Fig. 2) the following equations necessary for the determination of the primary phase currents are obtained:

$$\begin{aligned} J_0 - J_1' - J_2' &= 0 \\ J_0 - J_1' - J_3' &= 0 \\ J_2' - J_3' &= 0 \\ J_1' + J_2' + J_3' &= 0 \end{aligned}$$

From these equations the phase currents can be found:

$$J_1' = \frac{2}{3} J_0, \quad J_2' = J_3' = \frac{1}{3} J_0$$

These, together with the magnetising currents, give the line currents.

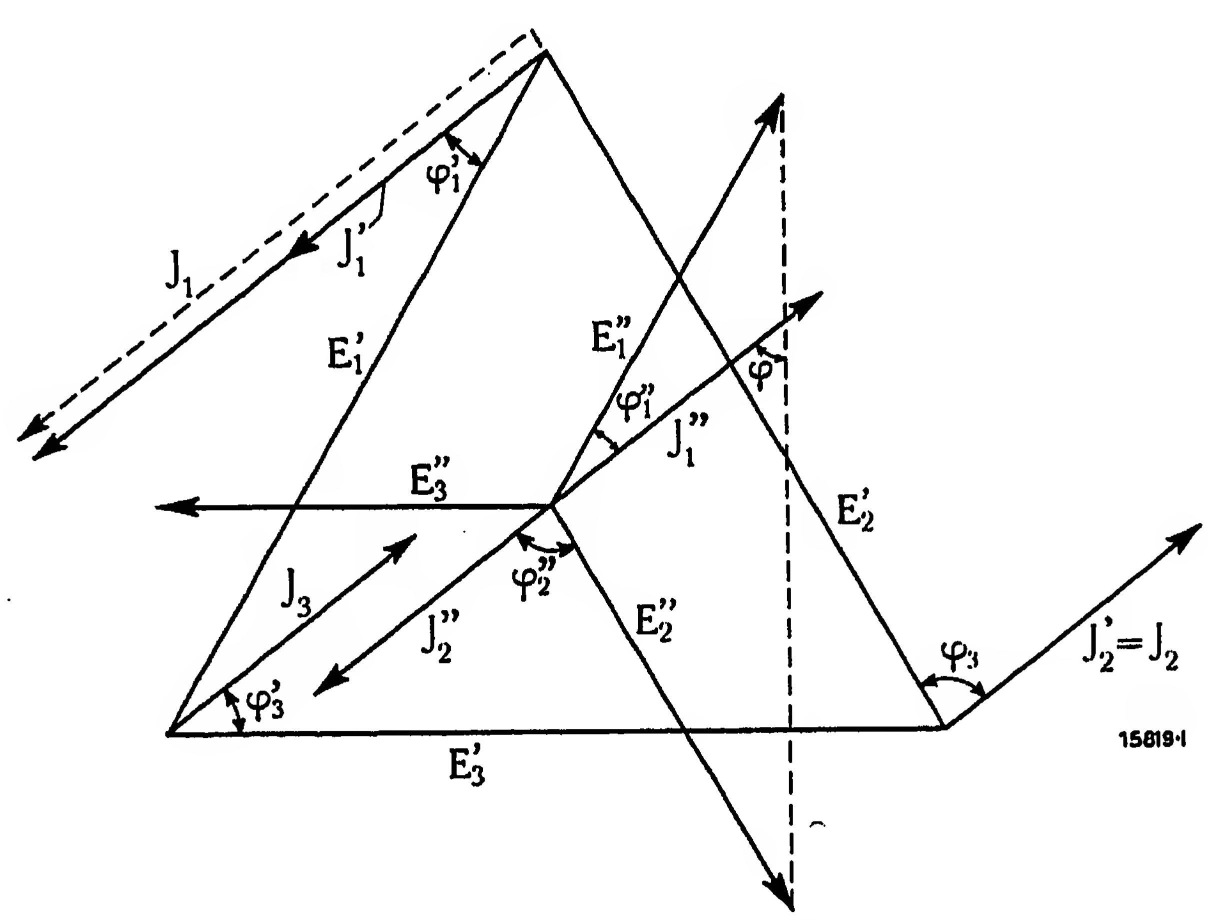


Fig. 6. — Vector diagram of a delta-star transformer with a single-phase load applied between two phases, no account being taken of the no-load current and the pressure drop.

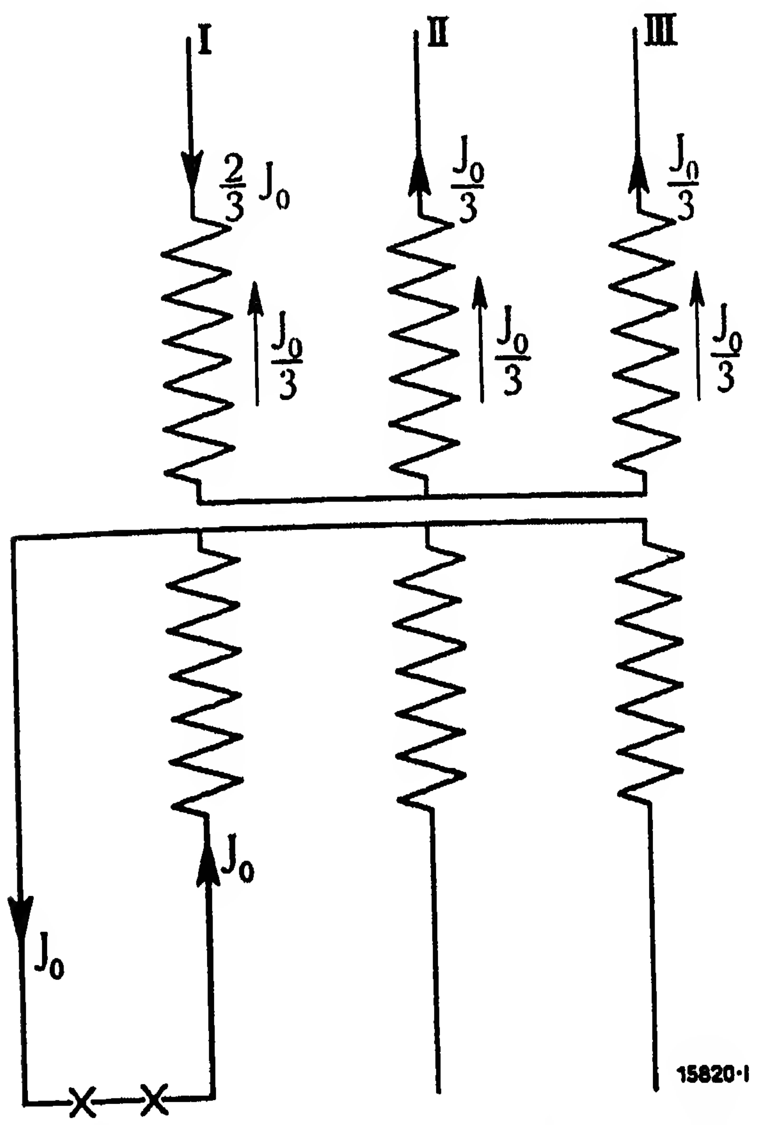


Fig. 7. — Distribution of current in a star-star transformer with a single-phase load applied between the neutral point and one phase.

The currents J_2' and J_3' act as magnetising currents in their respective phases, as they are opposed by no back ampere-turns. On the other hand, they constitute the back ampere-turns opposing the load current in the third phase.

These conditions result in very great magnetic leakage, and consequently in inadmissible pressure drops, so that the maximum extent to which the load on such a transformer may be out of balance amounts in practice to about 10—15 %.

The distribution of current shown in Fig. 7 for the case of a single-phase load on the secondary side corresponds to the values calculated above.

The resultant ampere-turns on phase 1 are represented by $(J_0 \cdot z - \frac{2}{3} J_0 \cdot z) = \frac{J_0}{3} \cdot z$ and have the same sense as those on phases 2 and 3, so that the magnetising ampere-turns are the same both in sense and amount in all three phases, as indicated by the arrows in Fig. 7.

Identical magnetic conditions can be obtained with a three-phase transformer by connecting the three primary coils in parallel, as shown in Fig. 8, and exciting them with single-phase current, the secondary remaining open. The pressure drop in each phase winding measured in this way, with a current $\frac{J_0}{3}$, corresponds to that occurring when a load J_0 is applied between one phase and the neutral point.

The results of such a test can be used to determine the extent to which the load may be out of balance, without pressure drops being involved in excess of the maximum allowable.

More balanced conditions are obtainable with star-star transformers if a third winding connected in delta is added. However, small transformers, such as those employed on lighting systems, are rarely constructed in this manner.

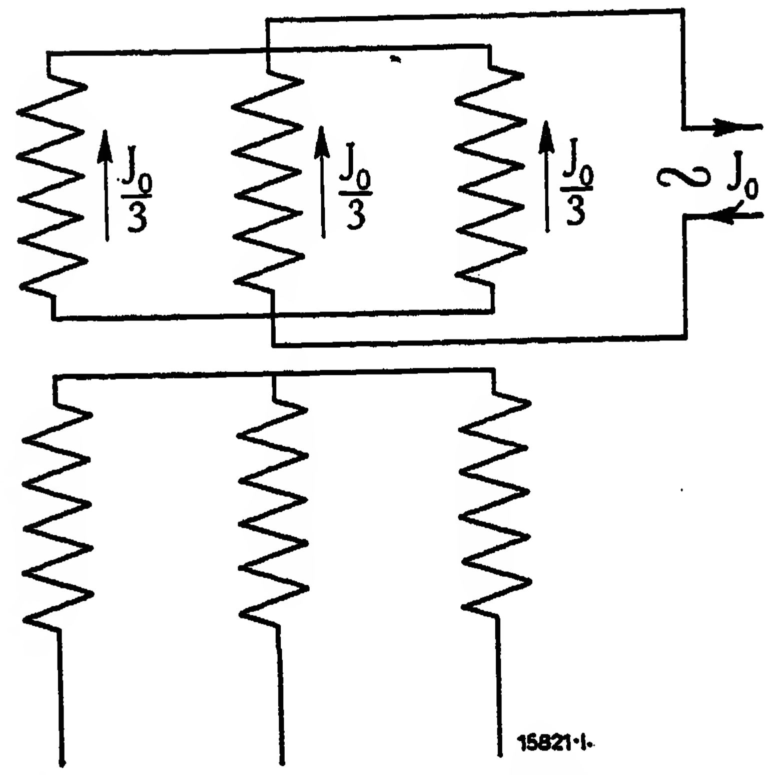


Fig. 8. — Connections for determining experimentally the pressure drop of a star-star transformer with unbalanced load.

Three single-phase transformers in star-star connection cannot be loaded between one phase and the neutral point, as the three magnetic circuits are entirely independent.

On the other hand, if a single-phase load is applied between two phases, the primary load currents are as follows:

$$J_1' = J_2' = J_0 \text{ and } J_3' = 0.$$

Each loaded phase has its back ampere-turns, so that the transformer can operate without excessive magnetic leakage.

From the foregoing, it is quite evident that transformers liable to any unbalanced loading must be connected in ⅄/⅄, △/⅄, or △/⅄ if they are to be utilised to the best advantage.

None of the various methods of connection have anything to do with the transforming of three-phase to single-phase current, but only with the effects of single-phase loading. Phase conversion is only possible by the use of rotary machines.

When a transformer is required to work in parallel with another already constructed, the choice of connection is often fixed beforehand by the way the latter is connected, so that the advantages of any particular arrangement for dealing with unbalanced loads may not be applicable. In planning a system, it is, therefore, of the greatest importance to take account of the influence of unbalanced loading on the transformers and to examine all the effects resulting from it.

F. Grieb. (G. T. S.)

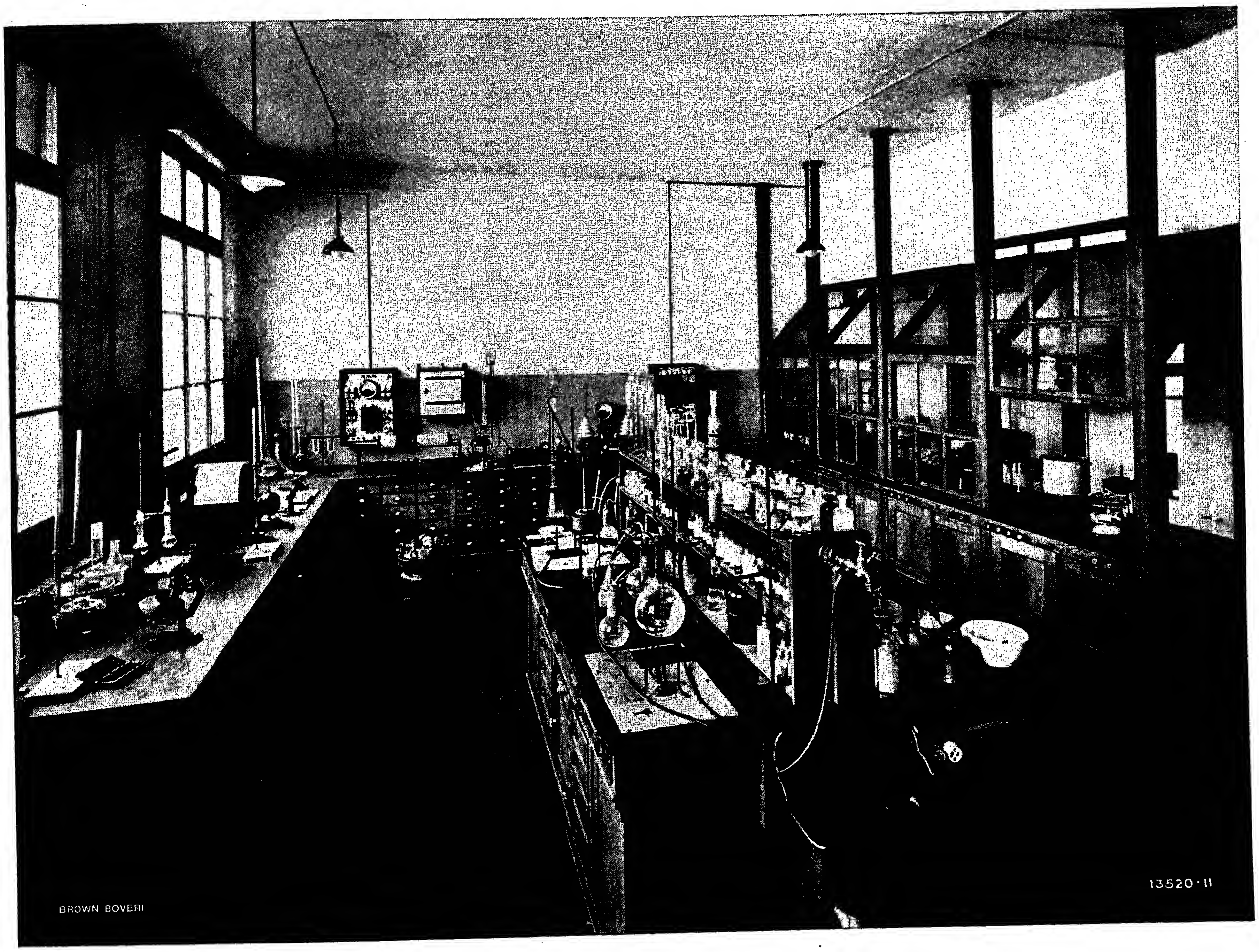
(MS 269)

Published by BROWN, BOVERI & COMPANY, LIMITED, BADEN (Switzerland). Printed by Kreis & Co., Basle.

VOL. IX AUGUST, 1922 No. 8

THE BROWN BOVERI REVIEW

EDITED BY BROWN, BOVERI & CO., BADEN (SWITZERLAND)



CHEMICAL LABORATORY, BROWN, BOVERI & CO., BADEN.
(Organic department.)

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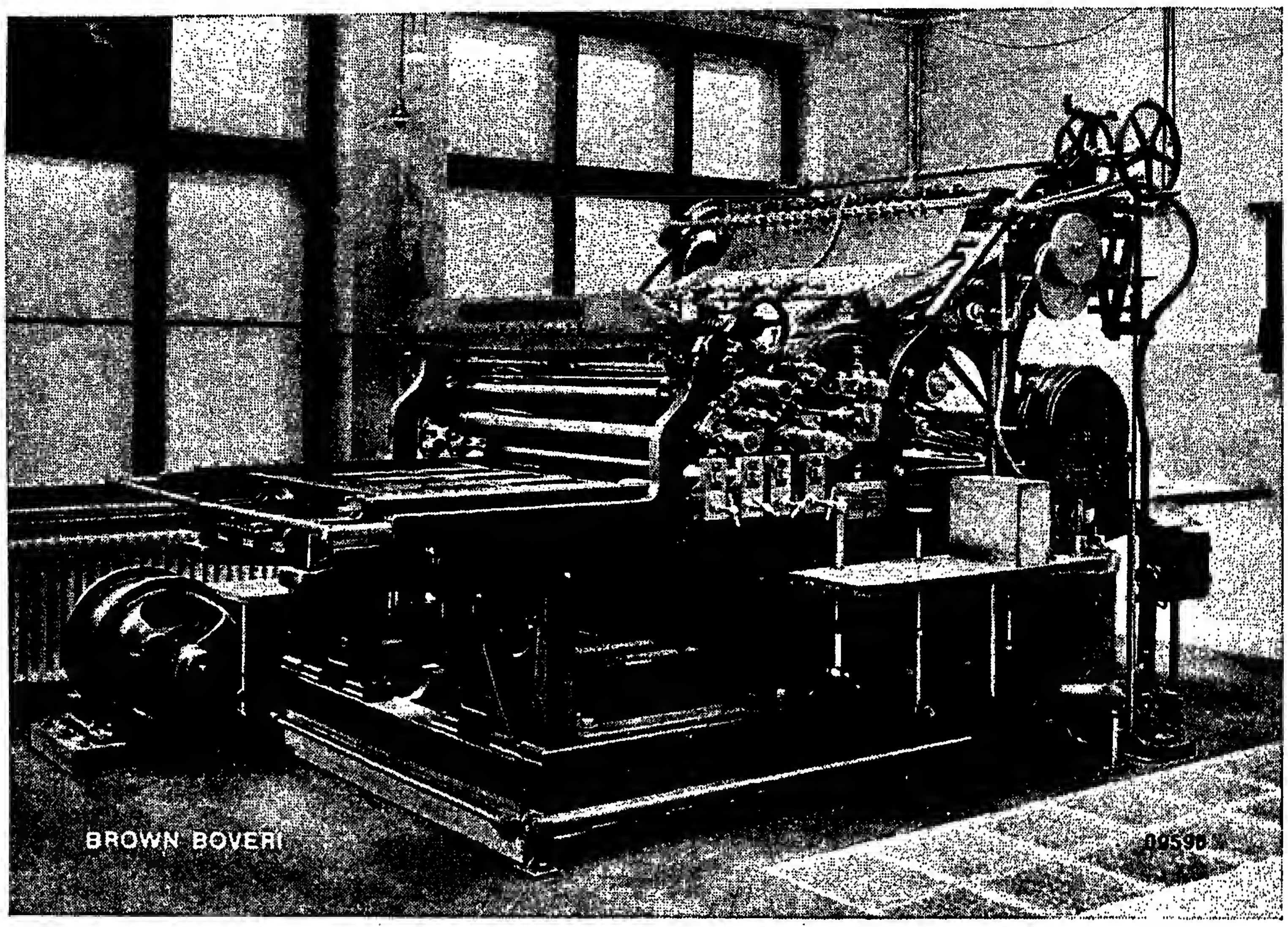

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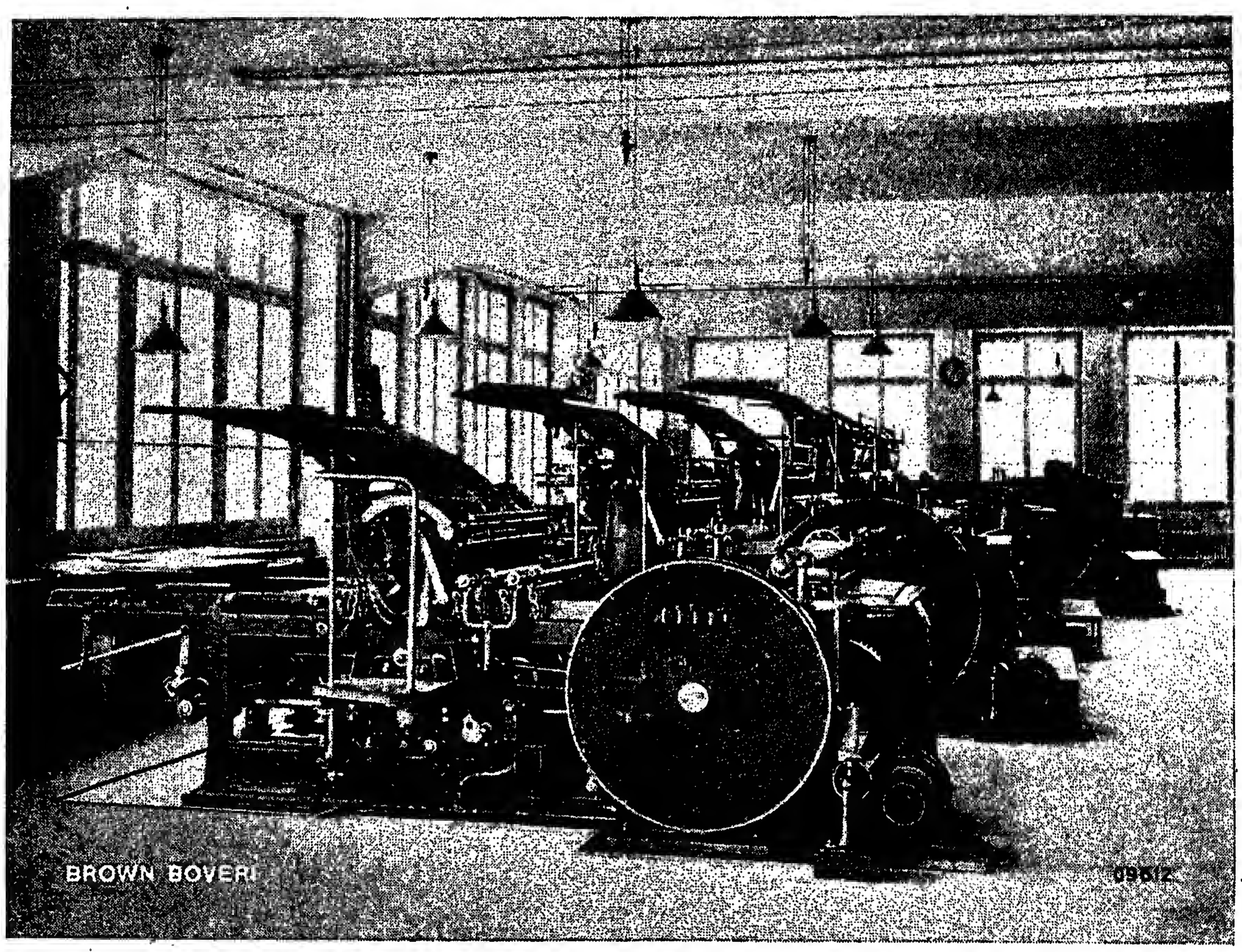

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THE HOUSE JOURNAL OF BROWN, BOVERI & CO., BADEN (SWITZERLAND)

VOL. IX AUGUST, 1922 No. 8

The Brown Boveri Review is issued monthly. Single numbers: 1.20 francs (1 shilling). Yearly subscription: 12 francs (10 shillings).

PROPERTIES OF TRANSFORMER OILS AND THEIR BEHAVIOUR WHEN HEATED.

Decimal index 620. 196.

MINERAL oils are most commonly used for transformers. As their name implies, they have a mineral origin, whereas vegetable or animal oils are extracted from organic tissues. The latter oils are chemically defined as complex organic compounds formed by glycerides or esters of fatty acids; mineral oils, on the other hand, do not belong, however, to any special group of organic compounds.

A brief survey of the origin and composition of transformer oils will not be out of place in this article, as the chemical composition is of paramount importance if the behaviour of these oils when subjected to heat has to be considered. The subsequent part of this article deals with the various methods devised in order to determine experimentally the properties of transformer oils when heated.

I. ORIGIN AND CHEMICAL COMPOSITION OF MINERAL OILS.

For many years, two principal theories have found acceptance for explaining the origin of petroleum, namely:

The *inorganic theory*, which was first put forward by Mendelejeff, assumes that metallic carbides have been formed by the action of carbon on iron or other metals. These carbides are decomposed under the influence of water at high temperatures and great pressures, and give off hydrocarbons.

Petroleum is produced, according to Sabatier's theory, by a molecular rearrangement of these hydrocarbons into compounds having molecules of considerable size (polymerous), which are produced by the action of water vapour and catalysts. By undertaking experiments under these conditions, Moissan was able to obtain hydrocarbons homologous to those found in petroleum.

The *organic theory* owes its inception to the optical activity of mineral oils, the explanation of which is not compatible with an inorganic origin. Engler and Hœfer consider that mineral oils are derived from the remains of animalicules and vegetable matter of the Paleozoic seas. Their putrefaction causes nitrous albuminoids to be decomposed, and form ammonia and soluble compounds. Only the more consistent derivatives formed by wax and grease remain, and constitute the basic materials entering into the formation of petroleum. Engler has succeeded in obtaining hydrocarbons from grease and wax without liberating any carbon. The experiment was carried out with a bent tube, which was soldered at either end. One portion of the tube was heated to 400^0 C in an oven, and the other contained a distilled mixture composed of benzine, petrol, lubricating oil and pitch. In all probability the natural formation of petroleum does not occur at such high temperatures; the time and pressures are, however, greater.

Marcusson explains the optical activity by means of his cholesterin theory. (Cholesterin is a complex alcohol, which is always to be found in animal fats. Phytosterin is a similar component entering into the composition of vegetables.) The products due to the decomposition of these stearines, which belong to the naphtenes or polynaphtenes have rotatory properties. The partisans of the inorganic theory consider that the optical activity is due to substances which have accidentally contaminated the oil.

Pontonié's theory gives a very satisfactory geological explanation of the origin of oil. According to his observations, the slime (sapropel), which is produced in stagnant waters, is the first stage in the formation of oil. Under such conditions, the elementary animal and vegetable[1] remains putrify, on account of the lack of oxygen, instead of rotting. The nonfatty bodies (albumens and cellulose) first of all disappear, so that what remains becomes correspondingly enriched in fatty substances. A grey-green

[1] The vegetable remains in this case are those of very elementary water plants (waterweeds, algæ), which contain a greater proportion of fat than the higher land plants, and therefore resemble animals in this respect.

pururient slime is first of all deposited which is transformed into a body with a firm and slaty structure (saprocoll) after having been subjected to pressure by the overlying layers. This transformation process is called bituminisation. Bitumen, therefore, is not a product due to modifications of vegetable and animal remains under exceptional circumstances, but is formed by phenomena which take place every day and exist concomittantly.

After secondary transformations of this solid bitumen have taken place, liquid petroleum is formed. Three different kinds of bitumina can be distinguished, namely, that which is completely soluble, that which is insoluble, and that which is partly soluble. These three classes of substance can be differentiated during the formation of sludge with transformer oils, which is, in reality, a bituminisation process. Further particulars are given in the paragraph dealing with the components of sludge.

Two distinct periods exist during this metamorphism:

(a) Transition from fatty resinous and waxy remains into insoluble, polymerous bitumen through soluble intermediate stages.

(b) Decomposition of these polymerous compounds under the influence of pressure and heat.

Engler has based his classification of bitumen on these changes and distinguishes between the following: —

1. Anabitumen, or bitumen in process of formation (sapropelic wax, pyropissit, fossilised wax), is soluble, and is composed of waxy esters and free acids containing more or less hydrocarbon.

2a. Polybitumen, an insoluble product (bituminous shale, Boghead coal) formed by polymerisation and condensation, contains polymerised hydrocarbons which are partially oxidised.

2b. Katabitumen, produced by katamorphism of polybitumen, becomes soluble under the influence of heat; it can also be derived directly from anabitumen.

3. Ekgonobitumen is petroleum composed of hydrocarbons with remainders of polymerous katabitumen or eventually of anabitumen.

4. Oxybitumen or asphalt results from the oxidation and polymerisation of ekgonobitumen or of one of the intermediate forms.

The entire process of metamorphism does not always comprise all these successive phases. The latter often overlap, and all the intermediate stages of the genesis do not necessarily occur one after the other. Hence, the multitude of final products which can be obtained and the considerable number of possible sequences of formation will be readily understood.

The simplest way of classifying petroleums is according to the source of their extraction (Pensylvania, Caucasus, Roumania, etc.).

Pensylvanian oils are chiefly composed of paraffinoid hydrocarbons and homologous substances such as isoparaffins (R_2 CHCHR$_2$, CHR$_3$, CR$_4$, where R designates a radical belonging to the so-called alkyl group). Besides these constituents, small quantities of benzol hydrocarbons (cyclic compounds) are contained in these oils.

Caucasian oils, however, are chiefly formed of cyclic combinations, such as naphtenes ($C_n H_{2n}$, cycloparaffin, etc. which are chiefly derived from cyclopentane) and aromatic hydrocarbons of compositions given by $C_n H_{2n-6}$.[1]

The widely-differing compositions of the various petroleums explain their completely dissimilar behaviour when heated in the presence of air, such as occurs, for instance, in transformers.

II. BEHAVIOUR IN TRANSFORMERS.

The modifications undergone by oils in transformers can now be examined, since the foregoing paragraph contains the necessary data for this purpose.

Three principal factors influence the phenomena to be considered, namely, heat, oxygen and copper. The temperature of the oil in a transformer is comparatively high and can attain 55 to 90° C and over, according to the mode of cooling. The oxygen of the air, which is in contact with the oil, has a considerable influence as an oxidant at such temperatures. Finally, copper is of considerable importance for the reactions as a catalyst for the oxidation, polymerisation and condensation phenomena which occur, although it only enters to a very limited extent into the composition of compounds (formation of acid naphtenous copper salts).

---

[1] In order to complete these particulars, mention may be made of the fact that ordinary tar has also a similar composition, and contains a considerable proportion of unsaturated cyclic hydrocarbons. Recently, naphtenes and very viscous oils have been obtained by low-temperature distillation of coal at temperatures ranging from 350 to 500° C. Only very small quantities, or no benzol at all, are obtained by low-temperature coking of coal, its place being taken by benzine. This process of distillation is undertaken on a large scale in order to extract the considerable quantities of bituminous hydrocarbons, which are found in tar obtained this way.

The considerable number of ways in which these three factors affect the formation of the derivatives produced by the decomposition of oils explains the diversity of their properties.

A first class of reactions is formed by polymerisation (transformation of a substance into another having a higher molecular weight) and condensation (rearrangement or concentration undergone when molecules arranged in an open chain form a closed cycle). The occurence of such reactions during the formation of mineral oils has been previously mentioned. At high temperatures and under the influence of oxygen contained in the air, the requisite conditions again exist for these transformations to take place, especially as certain preliminary conditions are already extant.

Besides the modifications due to polymerisation and condensation, attention must be drawn to the oxidation caused by the oxygen of the air and that dissolved in the oil, which is assisted by catalytic action of copper. Condensation can also occur in such cases. At the same time, however, acid compounds and corresponding intermediate products (aldehydes, ketones) are formed. An example of this description is afforded by the oxidation of olefines (unsaturated aliphatic hydrocarbons) which form alcohol if certain precautions are taken:

$$H_2C = HC_2 \rightarrow H_2C(OH) - (OH)CH_2$$

which then forms aldehydes, ketones and acids.

A rapid survey will now be undertaken of the most important compounds produced by these reactions.

Water. The action of oxygen on the oil causes water to be formed. It may be recalled here that sulphur, which belongs to the same group as oxygen in the periodic classification of elements, reacts in a like manner by causing sulphureted hydrogen to be liberated during the formation of asphalt. The same occurrence takes place with oils containing sulphur. Selenium, which also forms part of the same class of elements, reacts in a similar way, thus explaining the existence of selenious hydrogen without any oxygen.

Oxygen, however, also enters into the molecular rearrangements. Cyclic compounds containing oxygen are formed, which are similar to the example already mentioned of the oxidation of olefines.

Resins form a transient product in the transformation of petroleum into asphalt. They exist in a partly formed state in the majority of oils. Their presence causes the oils to have a dark appearance. They are easily dissolved by benzine, and the greater part remains in solution in oil.

Asphaltenes are derived from resins either by the inclusion of fresh molecules of oxygen (sulphur), or by intermolecular rearrangements and condensation (formation of closed chains and elimination of water), or finally by a molecular rearrangement only, without the presence of air. This group of compounds forms dark brown or black powders. Their specific weight is greater than unity. They are almost insoluble in benzine, but completely soluble in benzol.

Carbenes and carboides belong to a group which contains more oxygen and is darker coloured than the asphaltenes. They are formed by blowing air into mineral oil at 120^0 C. These compounds are partly insoluble, but have certain properties in common with the asphaltenes. Resins and asphaltenes, however, occur when only a small quantity of air comes into contact with the oil.

Further details on this subject will be given later on, when the different methods of examination of transformer oils are dealt with.

Asphaltic acids. Compounds with strong acid properties exist besides the more or less neutral substances enumerated above. These acids are found when examining the characteristic constituents — such as the amount of tar, quantity of incombustible matter, etc. — which serve to qualify an oil; they have a viscous and resinous consistency. After prolonged heating at 120^0 C the acids form anhydrides.

According to Marcusson the value of the molecular weight proves that these compounds derive from two molecules of high-boiling hydrocarbons. For this reason, they may be designated as polynaphtenic acids. Brauen[1] states that these acids easily form salts with lead in the oil tanks. The asphaltic acids appear to possess the properties of oxyacids. Highly-refined oils form acids similar to peracids, which are soluble in oil. (Peracids contain labile compounds of oxygen, and are therefore easily decomposed, and give off nascent oxygen. This decomposition can have very pernicious after-effects on the further oxidation of the oil and on the insulation.)

Brauen has also found that oils containing aliphatic compounds decompose more readily than those formed of cyclic compounds. On this account, the Caucasian oils are exceedingly stable.

The formation of sludge in transformers depends, therefore, on a great number of circumstances. These deposits considerably hinder the circulation in the cooling system and oil passages, and can have, consequently, disastrous consequences. Hence, it is of paramount

[1] Elektrotechnische Zeitschrift, 1914, p. 145.

importance for users to know the exact properties of their transformer oils. The various methods evolved for testing transformer oils by different electrotechnical societies will now be examined and criticised.

III. METHODS OF TESTING TRANSFORMER OILS.

(a) The sludge test. This method of examining the properties of transformer oils has been laid down by the Institution of Electrical Engineers[1]. It consists of drawing air through oil at a comparatively high temperature (150° C and over). Small pieces of copper are placed in the oil in order that the catalytic action of this metal shall be taken into account.

This test is carried out in practice by placing 100 cub. cm of the oil to be tested in a long-necked flask of 250 cub. cm capacity. The neck of the flask is surrounded by a tube through which water flows during tests. A condenser is thus formed which prevents volatile constituents from escaping. The flask is closed by a stopper traversed by two glass tubes, one of which reaches the bottom of the flask, while the other, which is short, is connected to a suction pump. The extremity of the longer tube, which is immersed in oil, is surrounded by a sleeve of fine copper gauze.

A suction pump, running at the rate of two strokes per second, draws air through the vessel. The air is made to go through a smaller bottle, which contains oil similar to that to be tested, in order to eliminate any impurities before entering the larger flask.

The flask is immersed in an oil bath which is kept at a constant temperature of 150° C by an automatic thermo-regulator and a stirrer. After the oil has been heated for 45 hours it is allowed to cool. The bottle is then filled with normal benzine and the contents are left to settle overnight; after this the oil is filtered through a paper filter (No. 589) which is then thoroughly rinsed with normal benzine. The residuum is dissolved in benzol and weighed once the solvent has evaporated.

The high temperature of 150°, together with the introduction of air in the presence of copper, assists the formation of acid derivatives. Completely erroneous conclusions may thus be deduced from tests carried out by this method. The formation of peracids and their decomposition can be very active — the rapid deterioration of cork stoppers, for instance, proves the intensive liberation of oxygen, and the energetic decomposition of the existing peracids at these high temperatures. A high degree of acidity is revealed, but only a small quantity of sludge is deposited. The nascent oxygen liberated by the decomposition of the peracids has also an influence as a very active oxidant. The sludge formed during a test of this description is therefore mainly composed of acid compounds, part of which form anhydrides at high temperatures. Moreover, the deposit also contains substances similar to the carbenes.

This method is not to be recommended, as the intensive oxidation of the oil has certain shortcomings, the chief of which have been already enumerated above. The formation of carbenoid sludge, especially, occurs only under very exceptional conditions in a transformer.

(b) The French prescriptions[1] take account of the quantity of sludge formed, and of the discoloration of the oil examined.

The tests have to be carried out as follows:— Ten to twelve grammes of the oil to be examined are poured into ordinary test tubes of 15 mm diameter, which are carried by a common support, and put in a double oil bath. The tank containing the latter is placed in a drying oven, which is provided with a thermo-regulator, and heated for 5, 50 and 135 hours. At the end of these periods, two test tubes are withdrawn so that the formation of sludge and the change of colour can be investigated. In order to ascertain the amount of sludge which has separated out of the oil, the contents of the tube are emptied on to a filter and rinsed with benzine having a density of 0·73. The filter and its contents are then exposed to the action of tetrachlorure of carbon in a Soxhlet until complete dissolution has taken place. Once the benzine has completely evaporated, the residuum is dried in a weighed platinum capsule at 90—100° C. Its weight is then expressed in per cent. of the initial weight.

The discoloration is determined by diluting the oil, from which all sludge formed during the heating has been removed, with amyl alcohol. This latter is poured out of a graduated burette until the oil regains its original colour. For this purpose, the oil is compared with untreated oil contained in a test tube of the same diameter before a ground-glass plate. The ratio between the volume of amyl alcohol added and that of the sample of oil gives the discoloration figure.

Erroneous conclusions can easily be drawn from this method, as no account is taken of the influence

[1] See the Report on switch and transformer oils, by W. Pollard Digby.

[1] "Cahier des charges pour la fourniture des huiles de transformateurs."

of copper and of the soluble sludges. Furthermore, the surface exposed to the air with test tubes of 15 mm diameter is very small and the duration of the test is not long enough. The results obtained this way are too favourable, and do not determine the quality of an oil.

(c) The German method, prescribed by the engineering societies of that country, consists of introducing oxygen into the oil to be examined, and of determining the tar content of the acid compounds thus formed. The latest prescriptions published up to date will now be described:[1]

First method (generally applicable).

1. 150 gr of oil are poured into an Erlenmeyer flask of 300 cub. cm capacity and placed in an oil bath at 120° C. Oxygen is let in slowly at the rate of two bubbles per second. The flask is closed by a cork stopper through which passes a pipe of 3 mm bore. The end of this pipe has to be 2 mm above the bottom of the flask. 50 g of oil are then treated in the following manner:—

2. An alkaline solution (Kissling) is added which has the following composition:— 1000 cub.cm of 96 % alcohol solution of caustic soda, 1000 cub.cm water and 75 g of purified sodium hydroxide. 50 g of this solution are mixed with the sample of oil. The mixture is then heated 20 minutes in a water (steam) bath and frequently stirred. The vessel is then vigorously shaken after an overflow pipe has been placed in it. The contents are now poured into a decanting funnel where they are allowed to cool and separate. The lower layer is then filtered through an ordinary filter into a small flask. 40 cub. cm of the filtrate remaining on the filter are placed in a decanting funnel with about 50 cub. cm of benzol and 20 cub. cm of hydrochloric acid (density 1·125) in order to give the mixture an acid tenure, and the contents are left to deposit. The lower layers are drawn off, and, after more benzol has been added, they are shaken in a second funnel. If the layer of benzol is still not clear after the second dilution, the alcoholic alkaline solution is saturated with common salt and diluted until it becomes clear. The decanting funnel is then rinsed out with benzol and twice washed out with water, but must not be violently agitated, as otherwise emulsions are formed. The benzol used for rinsing out the funnel is then poured into a weighed short-necked bottle of 250 cub.cm capacity. The bottle is closed with a pressed cork stopper of excellent quality, which is free from particles of cork dust. A steam pipe, which allows any vapour formed to escape, goes through this cork, and has an elbow immediately above the latter which is in connection with a cooler. The bottle is then placed in a water bath for which purpose a carrying ring with holes for letting through the steam is provided. The bottle and steam pipe are enclosed by a sheet iron cover, closed at its upper end, and having a hole for letting through the steam pipe. The water bath is then warmed so that the rising vapour heats the sheet-iron casing, and therefore the bottle and steam pipe at the same time, which thus prevents the benzol vapours from catching fire. Once the evaporation is finished, a small quantity of alcohol (absolute or 96 %) is added in order to remove all traces of water which may remain. The bottle is then opened and placed on its side on the ring in the water bath so as to allow of the heavy benzol and alcohol vapours running out. After this, the bottle is dried for five minutes in an oven at 100—105° C, allowed to cool, and weighed. The weight of residuum is multiplied by 100 and divided by 40 in order to express the tar content of the oil in per cent.

Acid compounds are formed by the introduction of oxygen and by the high temperature of 120° C. As already seen, peracids of the oxyacid group are thus obtained. The formation of an acid deposit only is a defect of this method. The other compounds which are produced by a less intensive oxidation do not occur, and the catalytic influence of copper is entirely neglected. The sludge which is insoluble in cold oil but dissolves in hot oil is also not taken into account — this kind of sludge is specially harmful to the cooling system, as the lower temperatures near the cooling pipes cause it to separate out and deposit; it thereby prevents the oil from being properly cooled. The proportion of soluble and insoluble sludge to the acid sludge differs from one sample to another. The tar content only gives an idea of one particular class of compounds derived from the oil, without giving any information as to the general nature of the sludge formed in a transformer.

The time taken by the first part of the test during which oxygen is bubbled into the oil amounts to 75 hours. Experiments were undertaken in the laboratory of the AEG transformer works in order to ascertain how the salts which are formed by the addition of Kissling's alkaline solution could be obtained in a more simple and rapid manner. The amount of compounds formed this way should correspond to half of the tar content obtained by following out the official

[1] See Elektrotechnische Zeitschrift, 1922, No. 5, "Transformatoren- und Schalteröle," by Dr. Georg Stern.

prescriptions. This simplified method, however, has been found to give misleading indications of the sludge formation on account of the inherent defects of the principles of this method which have already been given above.

Sodium peroxide[1] has been found to be suitable for oxidising oil. For this purpose, a known quantity of this very active oxidant is added to the oil to be tested. The first part of the procedure is, therefore, altered; 50 g of untreated oil are placed with 3 g of sodium peroxide.

The rapid oxidation enables the complete test to be carried out in four hours. The tar content obtained this way is always somewhat less than that given by bubbling oxygen through the oil. This difference is due in all probability to the fact that the composition of the compounds formed this way varies according to the intensity of oxidation.

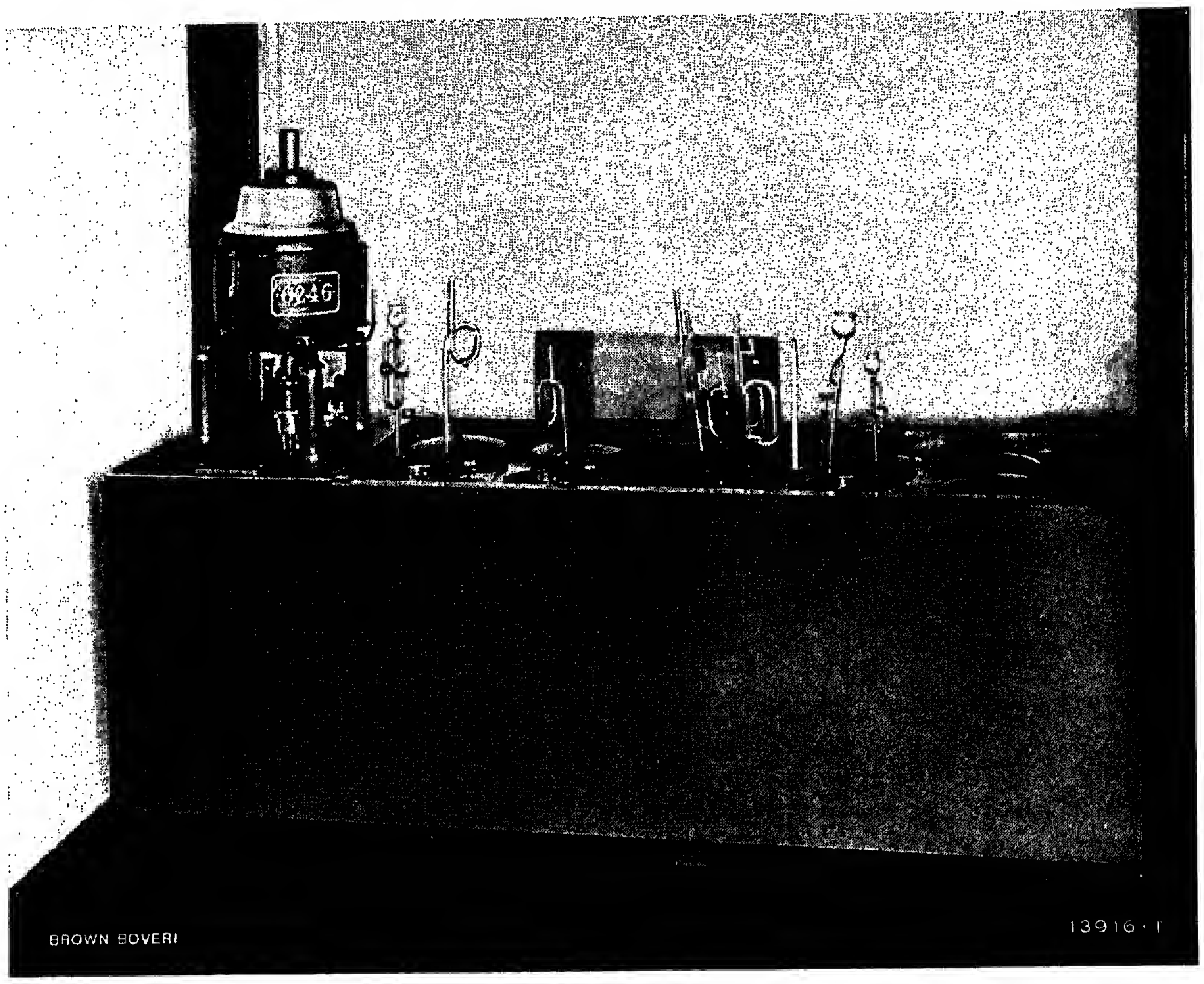

Fig. 1. — Apparatus for testing oil.

(d) The Brown Boveri method has been elaborated in order to overcome the shortcomings of the official tests for transformer oils laid down by the various engineering societies, and is the outcome of satisfactory experiments carried out in the laboratories of the firm. A short description of this method will now be given.

The oil to be tested is heated at 112° C in a copper tank, having a capacity of about 1·2 litres, into which air is allowed to penetrate. Ten of these vessels are placed in a large oil bath, which is heated by an electric heater with three positions for allowing the temperature to be adjusted, and is provided with a thermo-regulator and a motor-driven stirrer. An idea of the appearance of the apparatus can be gathered from Fig. 1.

About one litre of oil is poured into each of the copper vessels. Three copper needles of 2·1 mm diameter, wound round with normal cotton yarn 90/2 of known dielectric rigidity, are immersed in each vessel. A copper plate with six circular holes is placed on each tank. Three test tubes having a diameter of 16 mm are inserted into these holes and completely filled with oil. About 5 grammes of copper filings and a copper needle, similar to those mentioned above, only shorter, are also placed in each test tube to the top of which is fastened a tube which allows the oil to expand. Fig. 2 illustrates all the appliances which have just been described.

The contents of the vessel are now heated for 300 hours in the copper tank. The conditions thus obtained are closely similar to those to be found inside a transformer, as account has been taken of the presence of air as well as of the influence of copper and cotton on the oxidation phenomena. The proportion of copper to oil, however, is greater than in a transformer. The same conditions are realised in the test tubes which are immersed in the oil contained in the vessel, except that no air is admitted to the oil.

This way of carrying out the tests permits all the compounds derived from the oil to be examined in cases when air is admitted, as well as of the influence of cotton to be ascertained. The contents of the test tubes show whether any modifications occur when no air is allowed to come into contact with the oil.

It has already been mentioned that a certain number of the components which enter into the composition of sludge are to be found in untreated oils. The molecular rearrangements, which occur at high temperatures, cause sludge to be formed, which eventually separates out. Furthermore, the presence of copper enables the effect of this metal on the reactions to be followed, and its influence on the cotton winding, which envelops the copper needle, allows of an idea being formed of the extent to which the insulation is attacked.

[1] Dr. Brauen's method.

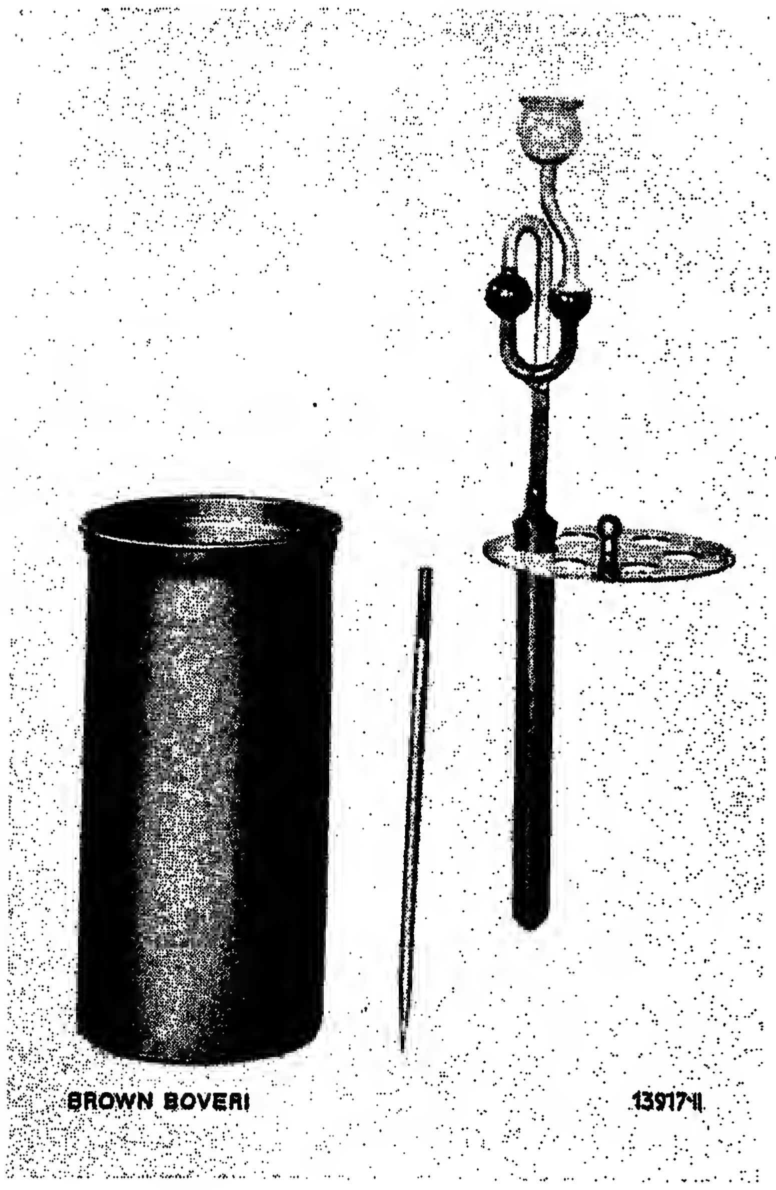

Fig. 2. — Copper vessel with appliances.

After heating for 100 hours, a test tube is taken out of an oil tank, and the colour of the oil it contains is compared with that of the untreated oil. The cotton yarn is removed from the copper needle, and 15 test pieces are made from it, which are submitted to traction tests on a special tensile testing machine for cotton (Fig. 3). The average increase or decrease of strength of the latter compared with that of cotton soaked in untreated oil is calculated. The influence of the immersion in oil can be ascertained this way. Samples of the contents of the copper tank are taken, and examined in a similar manner; the oil in this case, however, has been in contact with air. The same tests as in the foregoing case are repeated with the cotton yarn which is wound round the copper needles immersed in the tank. The oil is vigorously stirred with a glass rod, and a sample of about 35 cub. cm is taken in a test tube of 23 mm diameter, which is then corked and left standing a certain time so as to enable the sludge to deposit.

The same proceedings are carried out at the end of 200 and 300 hours. Complete information as to the modifications undergone by the oil during the test is thereby obtained. The volume of the sludge contained in each of the three test tubes is determined in per cent. of the volume of oil, 24 hours having been allowed for the former to deposit. The texture of the sludge, which can be flaky or sandy, is also recorded in order to obtain as complete information as possible concerning the oil. It has already been stated that part of the sediment dissolves in hot oil. The test tube is heated in a water bath at 70° C for this purpose, and the solubility of the sludge is ascertained. Dark-coloured opaque oils are illuminated with a small arc lamp in order to determine the sludge. The discoloration due to the heating of the oil is examined by comparison with a sample of the untreated oil.

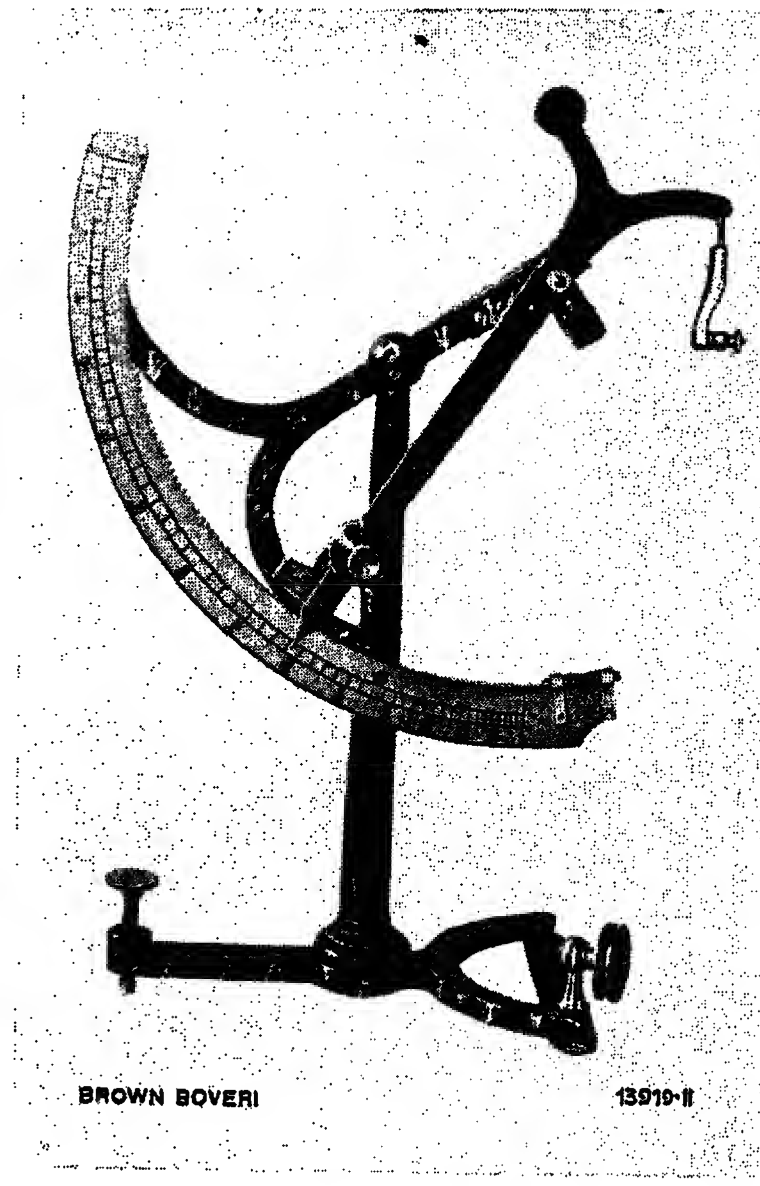

Fig. 3. — Tensile testing machine for cotton.

On comparing the results obtained by this method with those got by following out the official prescriptions in use in different countries, considerable discrepancies are found to exist. For instance, an oil, which was examined according to the rules laid down by the German prescriptions, was found to have a low tar content, whereas, the amount of sludge which separated out of the same oil was found to be considerable when treated by the Brown Boveri method.

The following table gives the results obtained from tests carried out according to the four different methods described with three different kinds of oil.

TABLE I.

	I	II	III
Specific gravity	0·9090	0·9110	0·9046
Viscosity* at 20° C	6·9°	6·74°	6·5°
„ „ 50° C	2·1°	2·1°	2·15°
„ „ 70° C	1·48°	1·51°	1·51°
Flash point	180° C	174° C	176° C
Ignition point	208° C	205° C	204° C
1. Sludge test	3·38%	2·23%	0·21%
2. French prescriptions:			
After 5 h at 150° C	—	—	—
„ 50 h „ 150° C	—	—	—
„ 135 h „ 150° C	0·204%	0·20%	0·18%
Colour: untreated	yellow-brown	yellow	yellow
After 5 h at 150° C	„	„	„
„ 50 h „ 150° C	red-brown	yellow-brown	yellow-brown
„ 135 h „ 150° C	black	black	dark red-brown
3. Tar content	0·53%	0·22%	0·22%
4. Brown Boveri method:			
After 100 h at 112° C	1·3%	1·2%	1·2%
„ 200 h „ 112° C	10·2%	11·7%	26·5%
„ 300 h „ 112° C	30·0%	19·5%	27·7%
Colour after 100 h	brown	brown	yellow-brown
„ „ 200 h	„	„	brown
„ „ 300 h	dark red-brown	red-brown	red-brown
Transparency after 100 h	clear	clear	clear
„ „ 200 h	„	„	opaque
„ „ 300 h	opaque	„	„

* Viscosity in Engler's degrees.

The first oil is evidently of inferior quality, as unsatisfactory results are obtained by all methods. The amount of sludge separated out by the French method differs only very slightly from one oil to another, the third oil giving the best results. Oils II and III have the same tar content when the oil is examined by the German method, but the amount of deposit obtained by the sludge test shows that the properties of these oils differ widely. The results of the tests carried out according to the Brown Boveri method show that the second oil is better than the third, whereas the smallest amount of deposit obtained with the sludge test was with the third oil.

These results conform with the conclusions already arrived at above, namely, that completely erroneous results are obtained when only acid compounds are examined. The acidity of the oil during the 300-hour test varied according to the figures given in the following table.

TABLE II.

	I	II	III
Acidity of the untreated oil	0·095	0·025	0·022
Acidity after 300 hours at 112° C	1·777	0·705	1·269

On comparing these values, it will be seen that the second oil gives the most favourable results when oxidised slowly. These figures serve to confirm those obtained by the Brown Boveri method given in Table I.

Figs. 4 and 4 b show the appearance of a good and an inferior oil. The two oils have the same tar content, but the amount of sludge formed by the Brown Boveri method of testing oils is completely different.

The long time required for heating the oil and the volumetric determination of the sludge are the principal defects of this method. Further research is being undertaken in order to obviate these objections. However, the second shortcoming has a valuable feature, as the compounds formed do not all separate out of the oil at the same temperature, and their quantity depends on the presence of air and copper.

IV. THE INFLUENCE OF TRANSFORMER OIL ON COTTON WHEN HEATED.

The quality of a transformer oil is characterised not only by the amount of sludge formed, but also by its influence on the insulation, which, in the case of transformers is usually of cotton.

By cotton is meant the fluffy down which envelops the seeds of plants belonging to the gossipium family. This down is formed by unicellular fibres of pure cellulose, which can be directly spun on account of their considerable length. These threads are further treated, and are made up into tape for insulating copper transformer coils.

As with the reactions which occur in the oil itself, those which are undergone at the same time by the cotton are of a very involved nature. In order to better understand these reactions, the composition of cellulose will be briefly examined.

Cellulose is a polymerous hydrocarbonate whose composition is given by $(C_6\ H_{10}\ O_5)_x$. According to the latest research, the factor x is not so great as was formerly assumed for substances having the colloidal properties of cellulose. Many different kinds of chemicals are used during the preparation of cotton fibre — such as those required for glossing in the weaving mills, and, later on, for dressing the cotton. The cotton used for insulating purposes must be free from all substances of this description, as the latter under the influence of heat can cause rapid deterioration of the cotton fibres, and, together with copper, can have a deleterious influence on the oil.

The oxidation of transformer oils causes acids to be formed, as already shown in the preceding paragraph. Cellulose is attacked by organic as well as inorganic acids, and forms hydrocellulose from which saccharates are derived. The action of acids produces a swelling of the fibres, together with the formation of cellulose hydrates. In the latter case, however, the strength of the fibres is increased, whereas the first class of reactions weakens them. Up to date, it has not been possible to isolate these compounds. The contingency of these two kinds of reactions affecting the dielectric properties in practice is remote, since the acids are too diluted and the organic acids only have a slight influence. The strength of cotton often appears to be increased by heating in oil; the microscope shows that the fibres are swollen. If paper is used for insulating instead of cotton, the same modifications occur, provided that cellulose paper is used, as is usually the case.

The insulating materials are chiefly attacked by oxygen. It may be recalled that peracids are formed, which contain unstable combinations of oxygen so that the latter is easily freed in the nascent state. The pernicious effects are chiefly due to the action of oxygen liberated this way; the fibres are transformed into oxycellulose and lose their strength,

PROPERTIES OF TRANSFORMER OILS AND THEIR BEHAVIOUR WHEN HEATED.

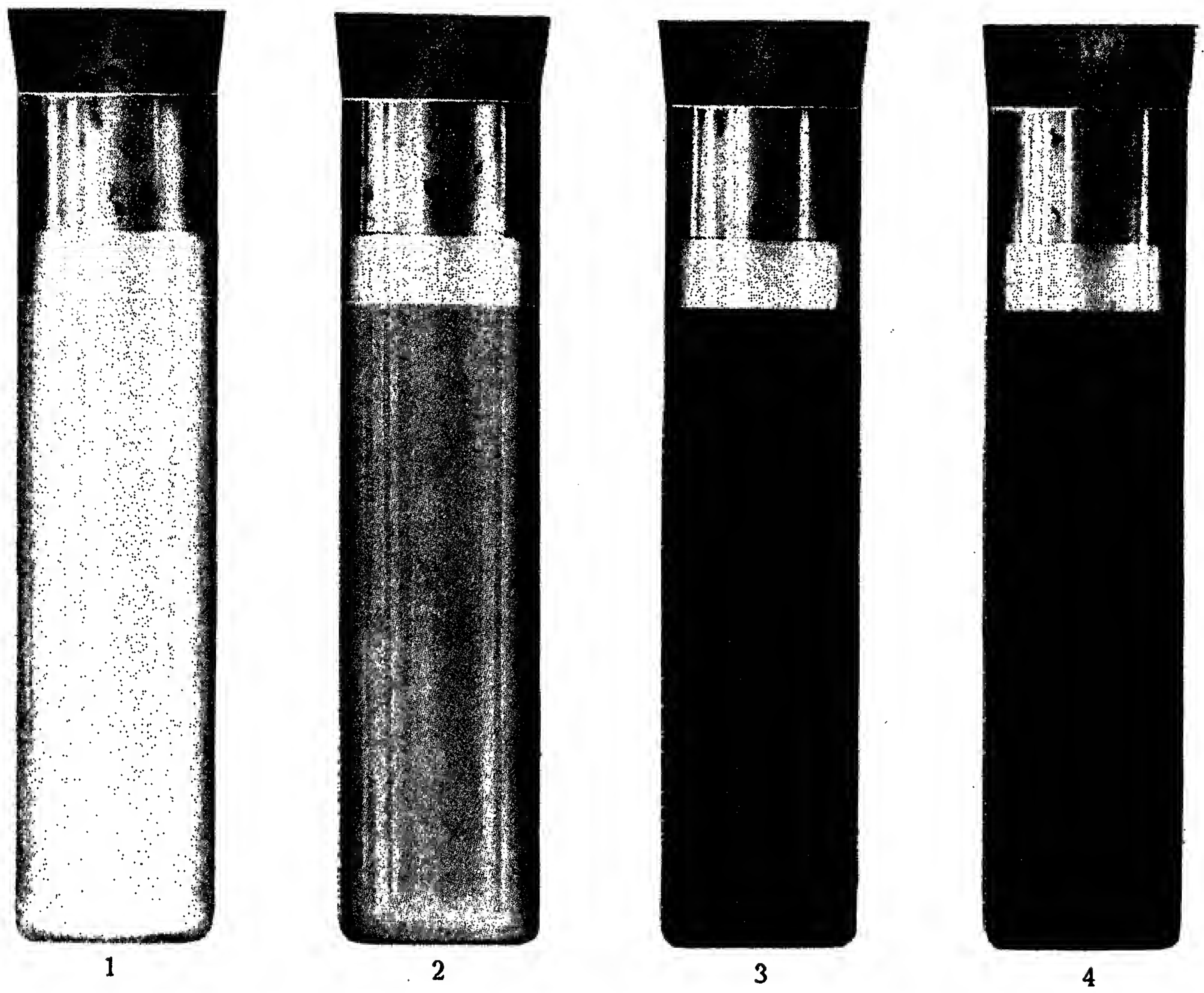

Fig. 4. — Good quality oil.

1. Untreated oil.
2. Oil after heating 100 hours at 112° C.
3. Oil after heating 200 hours at 112° C.
4. Oil after heating 300 hours at 112° C.

Tar content 0·12 %.

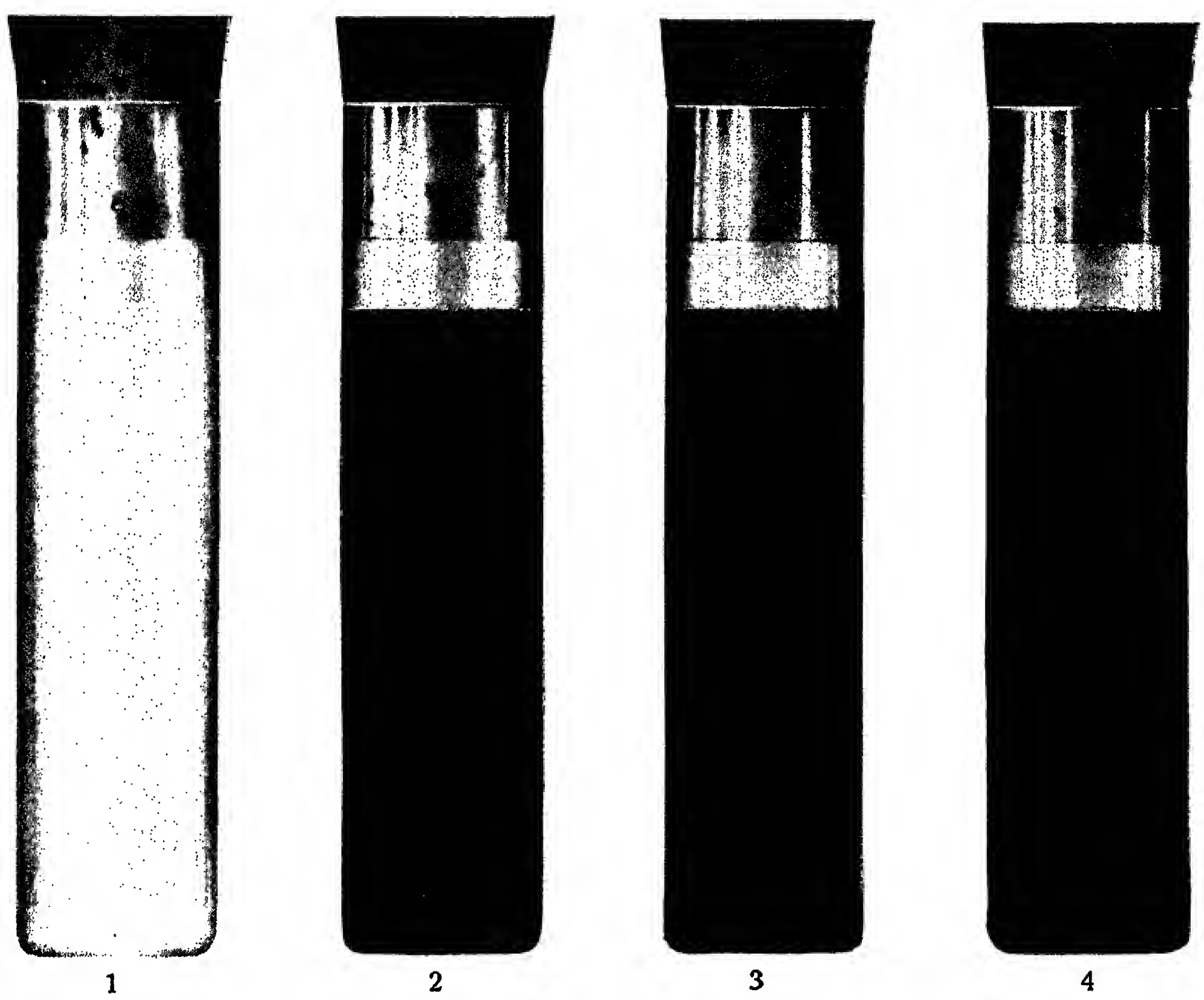

Fig. 5. — Inferior oil.

1. Untreated oil.
2. Oil after heating 100 hours at 112° C.
3. Oil after heating 200 hours at 112° C.
4. Oil after heating 300 hours at 112° C.

Tar content 0·12 %.

and, in certain cases, they crumble up and form a white powder. Such vigorous oxidation has been found to occur during the sludge test, when the cork stopper is destroyed by nascent oxygen.

These occurences must naturally be considered when tests are undertaken to determine the suitability of a mineral oil for transformers. No account is taken of then in the official specifications for transformer oils. With the Brown Boveri method these properties are determined as a matter of course. Their existence is also ascertained by a number of tests used in practice. The disadvantage of these other tests is that woven cotton is required, so that flaws which are produced by weaving are liable to lead to erroneous conclusions. This defect has been overcome in the Brown Boveri method, as a cotton thread of known quality and strength is wound round a copper needle. The diminution of strength undergone is determined for cotton immersed in oil heated in the presence of air as well as when the treatment takes place without air. The loss of strength is expressed in per cent. of the initial strength of the untreated cotton. It has been found that the decrease of strength does not depend on the formation of sludge, and still less on the tar content.

TABLE III.

	I	II	III
Initial stress	220 g	220 g	220 g
Stress at the end of 100 h at 112° C with air	201 g or 91·3%	179 g or 81·3%	190 g or 86·3%
Stress at the end of 200 h at 112° C with air	188 g or 85·9%	173 g or 78·6%	190 g or 86·3%
Stress at the end of 300 h at 112° C with air	185 g or 84·0%	140 g or 63·6%	140 g or 63·6%

The present state of knowledge is not sufficient for the theoretical explanation of the modifications undergone by cotton in oil to fully explained. The adjoining table will enable an idea to be formed of these variations in strength of the cotton.

These figures show that the first oil, in spite of its high tar content and large amount of sludge, does not attack cotton to any great extent. A considerable amount of acid sludge is formed, from which, presumably, no appreciable amount of nascent oxygen is liberated. A further proof is thus afforded that the formation of acid compounds alone does not suffice to determine the quality of an oil. The oils II and III have the same tar content, and both attack cotton in a similar manner. The total amount of acid formed is less with oil II than with oil III, as will be seen from Table II. It follows, therefore, that besides peracids — of which account is taken by the acidity of the oil, provided that they have not already decomposed into anhydrides — other peroxides can exist, the formation of which is due to oxidation of the cotton. It may happen that adsorption occurs as well as absorption proper, which may also affect the oxidation of the cotton.

Conclusion.

From the foregoing examination of the oxidation of transformer oils at high temperatures, it will be seen that one group of compounds alone is not sufficient to enable the quality of an oil to be defined. Account must be taken of the most widely-differing agencies so as to gather as much useful information as practicable. The Brown Boveri method of testing transformer oils has been worked out and elaborated in such a way as to fulfil these requirements as completely as possible.

Dr. H. Stœger (D. M.)

1500-VOLT ROTARY CONVERTERS FOR DIRECT-CURRENT RAILWAYS.

Decimal index 621. 313. 57: 621.331. 42.

Summary.

THE result of tests made with the first rotary converter for a pressure of 1650 volts, which can be considered satisfactory in detail as well as in general, demonstrate clearly that it is quite possible to build reliable and efficient 50-cycle rotary converters for pressures of 1500 volts and more for outputs as large as are required in substations of main-line railways. Moreover, on account of their low first cost, and their being able to recuperate the energy liberated on railways which employ regenerative braking, as well as to influence the three-phase system by phase compensation, they are, in many cases, the most suitable machines for converting alternating current into direct current.

It may also be mentioned that seven rotary converters for the Midi Railway of France are being built in the Brown Boveri Works at Munchenstein (Switzerland). One of these was completed and ready for testing in the extremely short time of four months after the first drawings were ready.

Introduction.

THE choice of 1500-volt direct current for the electrification of main-line railways, which has been made by the principal states of Western Europe,

has brought the manufacture of machines for producing direct current at this pressure to the forefront.

As the power required for traction purposes is not usually supplied by special power stations belonging to the railways, but by large interconnected central stations, the current of which depends on the sources of energy, electricity is very seldom generated in the form of direct current, but must be converted from 50-cycle three-phase alternating current, which is most frequently used for transmission over long distances and for distribution. The conversion takes place in substations disposed at suitable intervals along the track.

The motor-generator has hitherto been considered the machine best adapted for converting current at 1000 volts and over, chiefly on account of its reliability, flexibility and simple design. Nowadays, however, it is, in a great many cases, no longer employed, especially when great importance is attached to a high efficiency, and also when a transformer must be inserted on account of the high pressure of the alternating current, thereby entailing a further increase of the first costs of the motor-generator which are already high. Notwithstanding its rapid development and certain advantages over rotating converters, the power rectifier cannot always be taken as a substitute, as the important question of recuperation of power and phase compensation with rectifiers has not yet been solved.

Under these conditions, the desirability of using rotary converters for producing direct current at 1500 volts and over has been closely investigated — the technical experience gained in the course of many years of practice having been turned to account. Moreover, the rotary converter embodies the principal advantages of power rectifiers without having their inherent disadvantages, amongst which the difference in the first cost may be mentioned, in particular.

General.

Rotary converters can be used for converting alternating current into direct current, or vice versâ. As a rule, they are three-phase or six-phase, larger units being built almost exclusively for six-phase current.

The direct-current pressure is in a definite ratio to the alternating-current pressure at the sliprings, and has the following values:—

(a) *With three-phase rotary converters* (pressure across phases)

$$\frac{\text{Alternating-current pressure}}{\text{Direct-current pressure}} = 0{\cdot}62 \text{ to } 0{\cdot}65$$

(b) *With six-phase rotary converters* (diametrical pressure)

$$\frac{\text{Alternating-current pressure (open)}}{\text{Direct-current pressure}} = 0{\cdot}71 \text{ to } 0{\cdot}75$$

For this reason, transformers have nearly always to be utilised in plants with rotary converters.

In spite of the fixed transformation ratio between the pressure of the direct current and that of the alternating current, it is possible, by means of suitable appliances, to regulate the former within certain limits, which should be sufficient for the majority of cases met with in practice.

The rotary converter behaves like a synchronous motor in normal service; by over or under excitation, the phase difference between pressure and current can be altered at will. Consequently, the insertion of a reactance in the A. C. circuit, such as can be obtained with a choke coil or by artificially increasing the stray in the transformer, enables the pressure at the slip-rings, and therefore the D. C. pressure, to be varied by about 15 %. For more extended pressure variations, it is expedient to use induction regulators. A further advantage is the possibility of influencing the three-phase system by phase compensation through variation of the excitation.

Suitability of the rotary converter for high-pressure current.

Although it might seem that rotary converters can be designed for high pressures as easily as D. C. machines on account of their great similarity, this is unfortunately not the case. Neither does the widespread opinion prove correct that rotary converters, thanks to their small heat losses, can carry greater overloads than D. C. machines, because the capacity of modern and suitably designed commutator machines is limited more by the difficulties of commutation than by heating of the machine. With a given amount of material, the former prevent the output from exceeding a certain limit.

The maximum pressure for which a D. C. machine or rotary converter can be built for safe operation depends on the number of commutator segments that it is possible to insert between brushes of different polarity, since, for fulfilling the above conditions, certain limits are imposed by the average difference of pressure between the commutator segments. The more the distance between two adjacent brushes of different polarity can be increased, the higher will be the permissible maximum pressure. The distance between the brushes can be expressed as:—

Commutator circumferential velocity
Twice the frequency.

In other words, the distance between the brushes with a 25-cycle converter can be twice as large as with a 50-cycle machine for the same circumferential velocity of the commutator. Whereas, with D. C. machines the frequency can be chosen so as to suit the requirements, the rotary converter has to have the same frequency as the feeding system. Therefore, the maximum pressure at a given frequency in the case of the rotary converter is dependent only on the commutator circumferential velocity, on the subdivision of the commutator segments, and on the average difference of pressure between the latter.

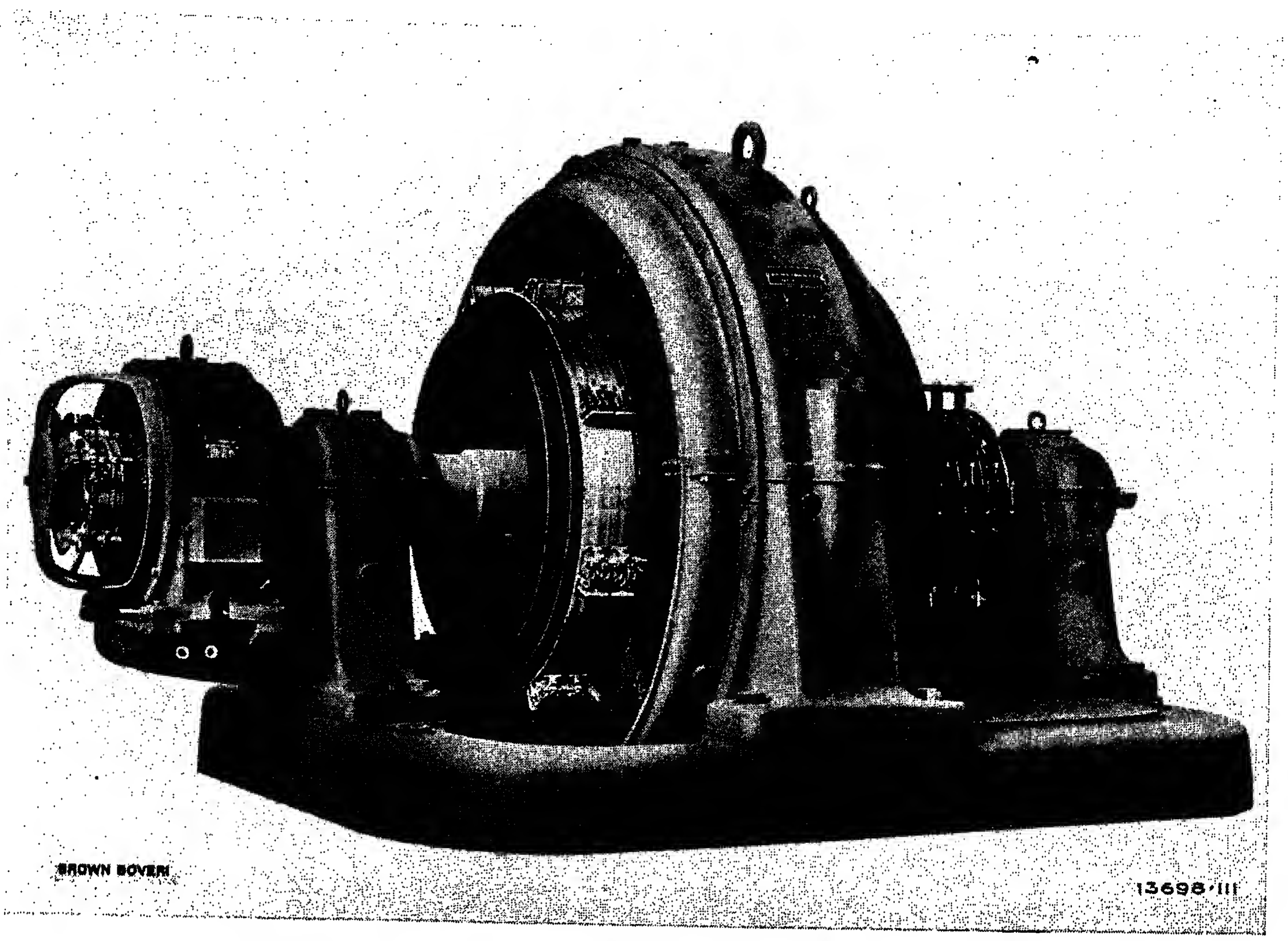

Fig. 1. — Rotary converter, 750 kW, 1650 volts D. C., 50 cycles.

It is still often assumed that it is not possible at the present stage of technical development and with the permissible values of the three principal factors (commutator circumferential velocity, subdivision of the commutator segments, and average pressure between the latter) to build reliable converters for pressures above 1200 volts per machine at a frequency of 50 cycles. As far as known, rotary converters for pressures much above 1200 volts at 50 cycles have never been used until recently.

To solve this problem, it has been necessary to break away from the old and accepted traditions, and to take a step forward. The following remarks have been written in order to dispel any doubts in this respect, and to show that the above-mentioned limit can be safely exceeded, provided care is given to the manufacture, and the design has been carefully thought out.

The Brown Boveri Rotary Converters for the Midi Railway of France.

This railway company ordered for their substations seven rotary converters from Brown, Boveri & Co., some of which have already been delivered. All the requirements called for in the specification have been successfully met, although these were very severe. The rotary converters are destined for operating in parallel with power rectifiers installed in neighbouring substations. Moreover, they have to be capable of returning to the A. C. system the electrical energy produced by regenerative braking when travelling down inclines. Each rotary converter has been designed to fulfil the following requirements:—

Continuous output	750 kW
Two-hour ,,	1125 kW
(following on a continuous full load)	
Five-minute output	2250 kW
(following on a continuous full load)	
No-load pressure	1650 volts
Speed	750 r. p. m.
Frequency	50 cycles.

As will be seen from these particulars, the requirements regarding overload capacity are exceedingly stringent; also, the other conditions are much more severe than the guarantees which have generally been specified until now. For instance, the rotary converters must be able to withstand five consecutive direct short circuits at intervals of 60 seconds. Fig. 1 shows such a converter after leaving the test bed where it had been subjected to severe tests.

To meet the exceedingly difficult conditions at overloads, the parts particularly subject to heating are effectively cooled by a careful arrangement of the ventilation. Provision is made that no carbon or metal dust from the slip-rings can penetrate into the interior of the machine. By suitably dimen-

sioning all essential parts coming into consideration for good commutation, and by adopting the Brown Boveri patent design of commutating poles, good operation is ensured even at the highest loads. Special attention is paid to the protection against short circuits, which are inevitable in railway service. In such plants, it is usually attempted to safeguard rotary converters against the effects of short circuits by a judicious choice of the protective apparatus; the machines in question, however, are able to withstand these occurrences on account of their correct dimensioning, ample distancing and suitable arrangement of all current-carrying parts, so that even direct short circuits cause no damage whatsoever should the protective apparatus provided on the D. C. side fail.

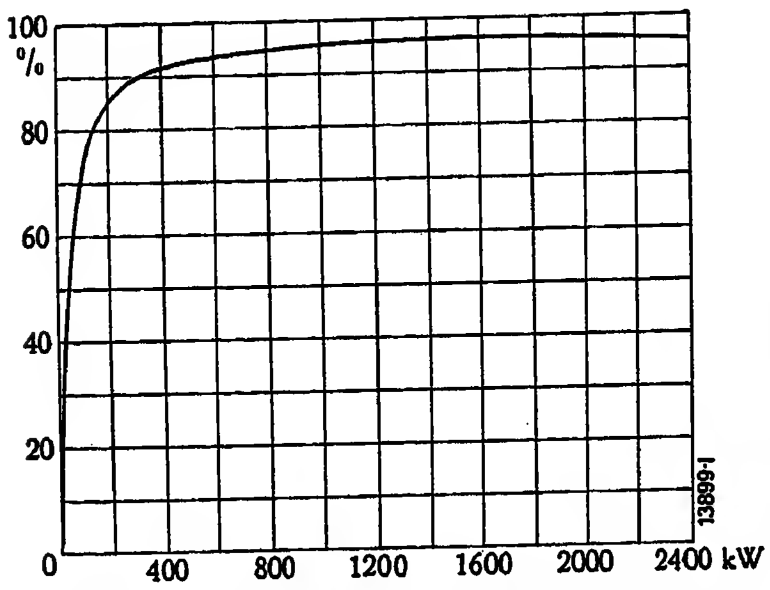

Fig. 2. — Efficiency curve of a rotary converter, 750 kW, 1650 volts D. C., 50 cycles.

In spite of the high circumferential velocities that are inevitable with rotary converters for such a high pressure, the machines run very smoothly, and do not produce any noise that might be disagreeable to the neighbourhood.

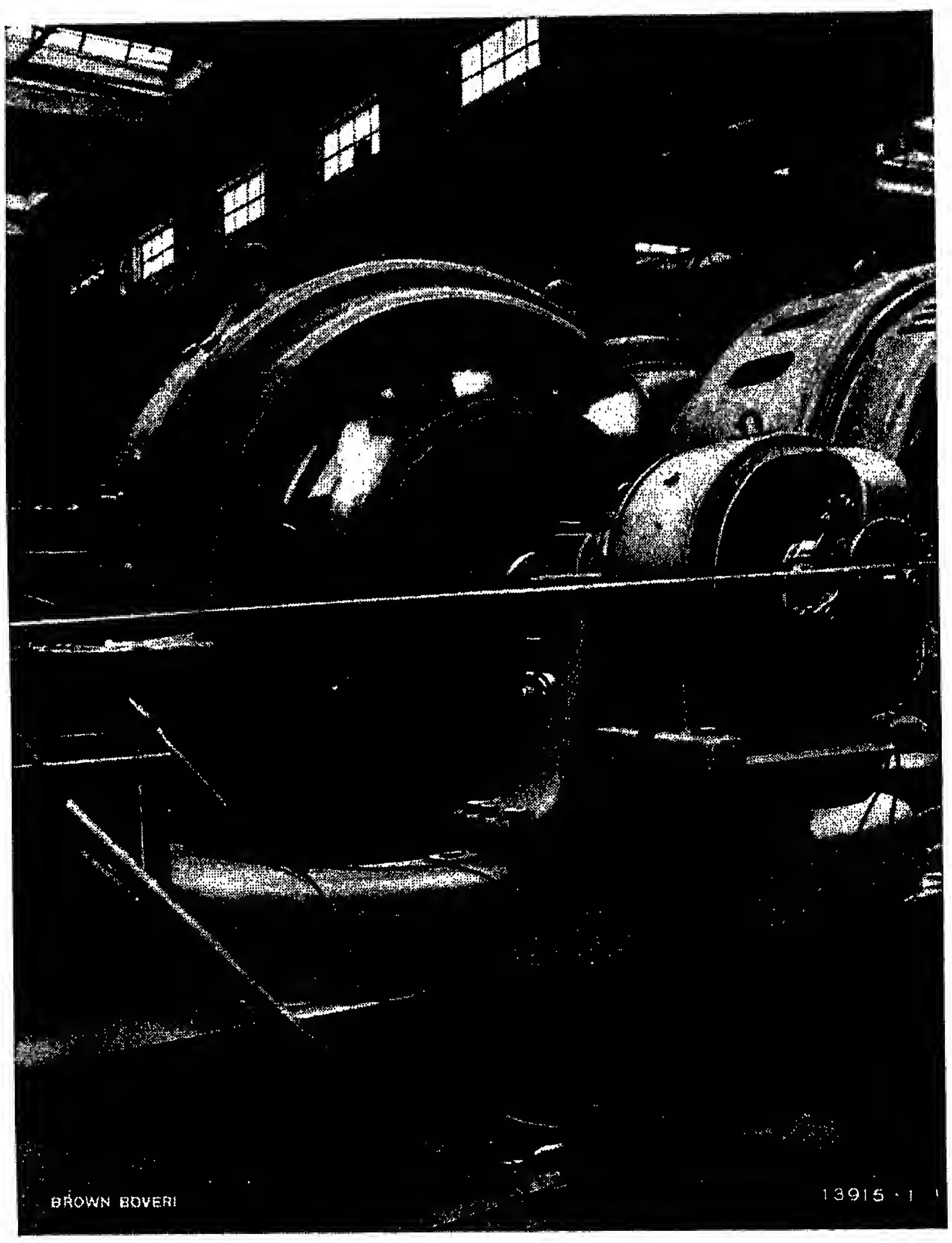

Fig. 3. — Rotary converter during a short circuit.

The appearance of these rotary converters does not differ greatly from that of machines of normal design and for lower pressures. A pleasing appearance has been obtained in spite of the excellent insulation and liberal distancing of all bare current-carrying parts. It is not necessary to insulate the machines from the earth, since all windings are insulated against the frame for the full pressure.

The field current for the rotary converters is generated by an overhung exciter, which enables the correct polarity to be always obtained at synchronism without using any auxiliary apparatus. Starting-up can be undertaken from the A. C. side by means of a starting motor which is provided with a flexible coupling. Synchronising takes place by means of an ordinary synchronising device, or simply and automatically by inserting a so-called synchronising choke coil between slip-rings and secondary terminals of the feeding transformer. This procedure is particularly suitable for automatic substations with large converters for which asynchronous starting is not admissible.

Experimental results.

The first high-pressure converter of this description built by Brown, Boveri & Co. was thoroughly tested in the Baden works. All conditions occurring in traction service, as far as these could be imitated with the means available on the test-bed, were taken into account. The tests were satisfactory in every respect and those that are of general interest are briefly described hereafter:

1. By adopting the above mentioned starting method with starting motor and synchronising choke coil, it was possible to start up and parallel the rotary converter in about 70 seconds. Only three switching operations are necessary for this purpose, namely:

(a) Switching-in the high-pressure switch on the transformer. (This enables the starting motor to bring the rotary converter to full speed. Synchronising is then effected automatically with the correct polarity.)

(b) Disconnecting the starting motor from the system.

(c) Short circuiting the synchronising choke coil.

The whole starting process is very simple, and no specially trained operators are required.

Direct starting tests with reduced pressure and the rotary converter starting as an asynchronous motor also gave favourable results. By making some trifling alterations, this method of starting could also be adopted for converters as large as those considered in this article.

2. Measurements have shown that the total no-load losses, including those of starting motor, amount to about 33 kW.

3. The efficiencies ascertained by the single-losses method have been plotted out in Fig. 2. Mention must be made in this connection that the values for loads equal to about half of the nominal output appear to be small. But when it is remembered that 750 kW represent only a nominal output which corresponds to the mean value of the load characteristic of the railway, and that the actual continuous output of the type of machine under consideration is 1200 kW, the values of the efficiencies for partial loads are displaced in a favourable direction. On assuming the output of the machine to be 1200 kW, the no-load losses measured amount to only 2·75 %, which must be considered extremely low for rotating converters.

4. Part of the continuous and overload tests which were combined with measurements of the temperature rise, were carried out at pressures up to 1800 volts.

5. For the recuperation tests, the rotary converter was connected on the D.C. side in parallel with two D.C. machines of corresponding pressure, and the load was varied by changing the excitation of the latter. No further auxiliary plant or alterations on the rotary converter were necessary for this purpose.

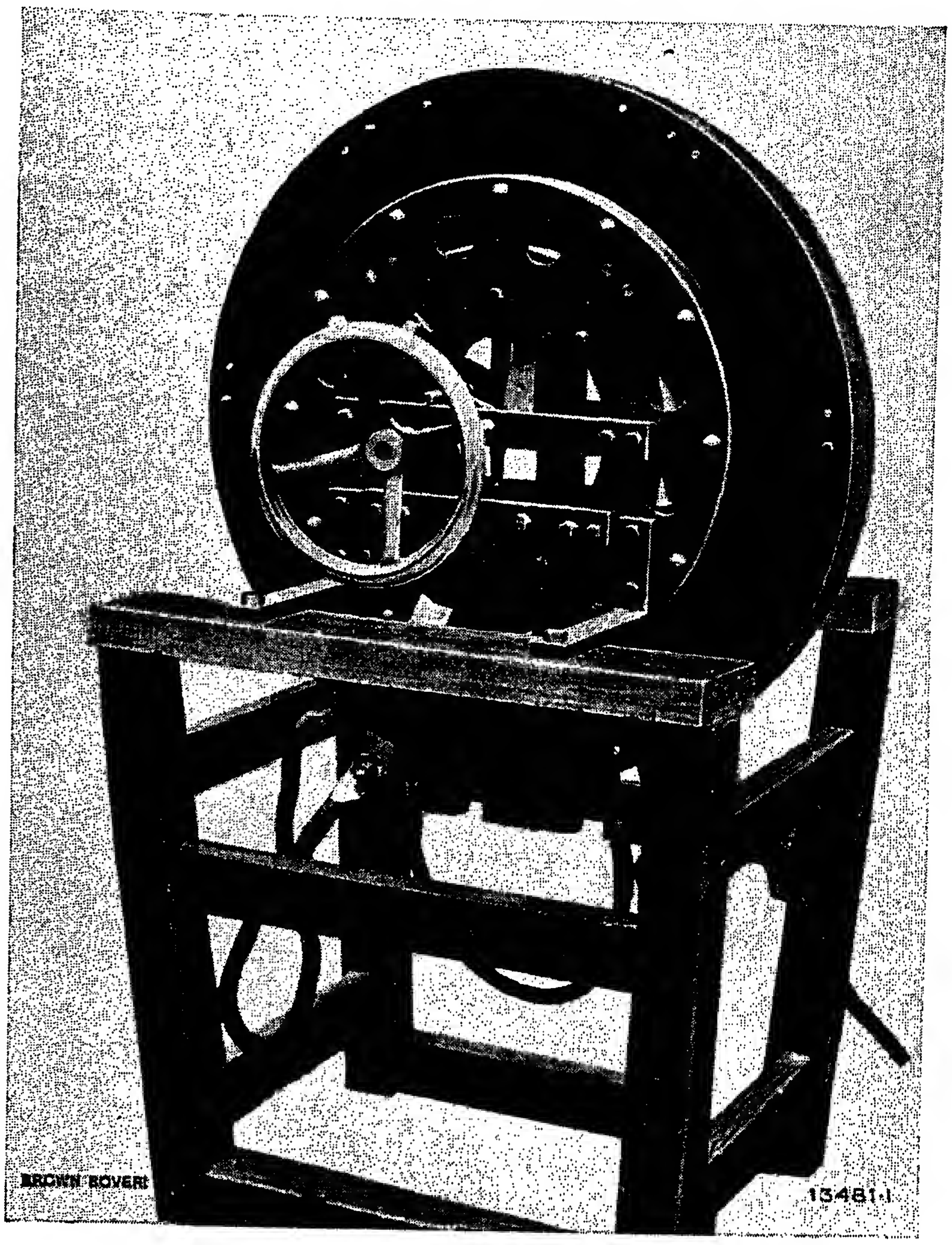

Fig. 5. — Quick-acting D. C. switch.

6. During the short-circuit tests made with the assistance of a Brown Boveri quick-acting D. C. switch, not only were the prescribed five direct short circuits carried out without the slightest difficulty, but the machine easily withstood more than twenty of them at intervals of about sixty seconds without the commutator or brush gear requiring the slightest attention.

All the short-circuit tests were made at full pressure, both in the case of the converter on load and when running light. After interruption of the short circuit, the converter continued to run normally in each case. More than 150 short circuits were made with the first machine built. In no case was it found necessary to overhaul any part of the rotary converter, which would have entailed a prolonged interruption of service.

The more or less heavy brush sparking in the case of such short circuits did

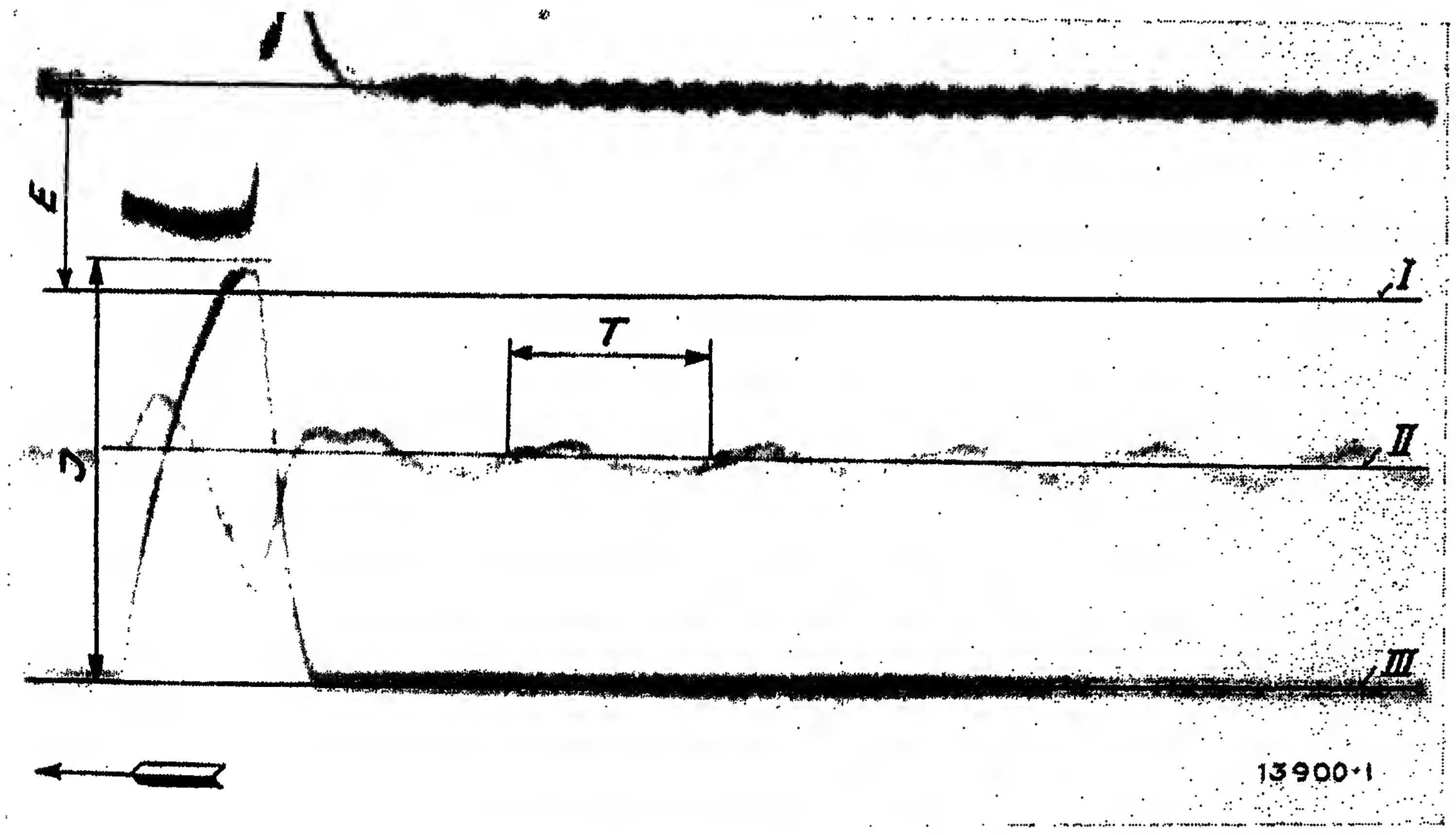

Fig. 4. — Oscillogram showing the variations of current and pressure of a rotary converter during a short circuit.

I. Zero line for direct-current pressure. E = 1650 volts D. C.

II. Zero line for alternating-current pressure. $T = \frac{1}{50}$ second.

III. Zero line for direct current. J = 6200 amperes D. C.

The arrow indicates the direction in which the film was wound.

not harm the rotary converter in the slightest. Fig. 3 shows this phenomenon on a rotary converter during a short circuit when using a quick-acting D. C. switch at about 1600 volts and a fundamental load of about 250 A direct current.

The variations of the current and pressure during such occurrences are shown in the oscillogram Fig. 4, which also indicates the extremely small interval for switching-out required by the quick-acting D. C. switch.

Fig. 5 shows the Brown Boveri quick-acting D.C. switch used for the short-circuit tests. Besides these tests carried out chiefly for checking the guarantees, further close tests were made, details of which will be published later on. *N. Widmer.*

ECONOMIC ADVANTAGES OF POWER-FACTOR COMPENSATION BY MEANS OF PHASE ADVANCERS.

Decimal index 621. 312. 0065.

THE disadvantages of generating and distributing electrical energy with a low power factor are sufficiently well known. The higher current increases the electric losses, decreases the power the system can transmit, and makes it more difficult to maintain the pressure constant, especially in the remote parts of the system. The user of electric energy who does not generate his own current is not directly affected by these disadvantages, unless the price he has to pay for the energy consumed is made to depend on the power factor. The present tendency — at least in the case of large consumers — is to make the price per unit vary according to the power factor. Thus, the increased costs due to a low power factor are borne by the consumers responsible for them. It is therefore of interest to such users to improve their power factor.

The first means of realising this consists in having induction motors of a power suitable for the duty required. Very often, in order to be on the safe side, motors are chosen with too great a margin of power; consequently they always run only partially loaded, with a correspondingly low power factor. Motors which are running light should be switched off at once even if the power they absorb is low.

Although a certain improvement can be made with care in such matters, the power factor cannot be raised above a certain limit. This limit is often very low, especially with an installation comprising slow-speed motors or a considerable number of small motors.

The power factor can be still further improved by connecting static condensers to the system. In European practice — at least for large plants — they have as yet hardly ever been employed. Another means of improvement is afforded by synchronous motors, which take a leading current when overexcited. According to requirements, these motors can be employed to give a useful mechanical output or be run light for the sole purpose of correcting the power factor.

In certain cases, three-phase induction motors have been replaced by three-phase commutator motors, as the latter work with a higher power factor. A very effective means of improving the power factor consists in fitting a phase advancer in the rotor circuit of a slip-ring induction motor. The phase advancers built by Brown, Boveri & Co. belong to this class.

The adoption of a phase advancer naturally entails a supplementary outlay, and it is now proposed to investigate by means of examples what savings can be made by improving the power factor — this improvement being obtained by the use of a Brown Boveri phase advancer — when the price of the current is made to depend on the power factor. A brief comparison of the various methods of phase compensation is made at the end of the article.

Consider a three-phase plant consisting of two 300-kW induction motors with an input of about 325 kW each. By means of a phase advancer, the full-load power factor can be raised from 0·9 lagging to 0·96 leading. Each motor takes, therefore, a lagging wattless kVA component amounting to 160 kVA without a phase advancer, whereas, when such a machine is fitted, the wattless component drawn from the system is leading and amounts to 90 kVA. By this means there is a saving in the lagging wattless kVA consumed of 2×250 kVA. Moreover, the phase advancers can be driven by D. C. motors, and the speed increased by hand regulation when the load on the main motor diminishes, so that the improvement is more pronounced at light loads. Thus, the rotor current of the induction motor remains within permissible limits, as the increase of the wattless current is compensated by the

diminution of the watt current. On a partial load, with an input of 200 kW per main motor, the power factor is corrected with a phase advancer from 0·87 lagging to 0·73 leading. Each motor without a phase advancer absorbs 115 lagging wattless kVA, and 185 leading wattless kVA with one; so that there is a saving of 2 × 300 lagging wattless kVA. As no pecuniary advantages are gained by having a leading current, it may seem that the raising of the power factor is to no purpose. If, however, the plant comprises other motors with a low power factor, the resultant power factor can be lagging, although that of certain machines is leading, and every reduction of the wattless component decreases the cost per unit. Suppose that the total power consumption of all the other motors of the plant under consideration is 850 kW, and their resultant power factor is 0·71, then 850 lagging wattless kVA are required. The whole plant takes 1500 kW when the two larger motors are fully loaded, and 1250 kW when they are on the partial load considered above. With the 1500-kW load, the power factor of the whole plant is 0·79 without phase advancers and 0·91 with the two phase advancers. With the 1250-kW load these values become 0·76 and 0·93 respectively.

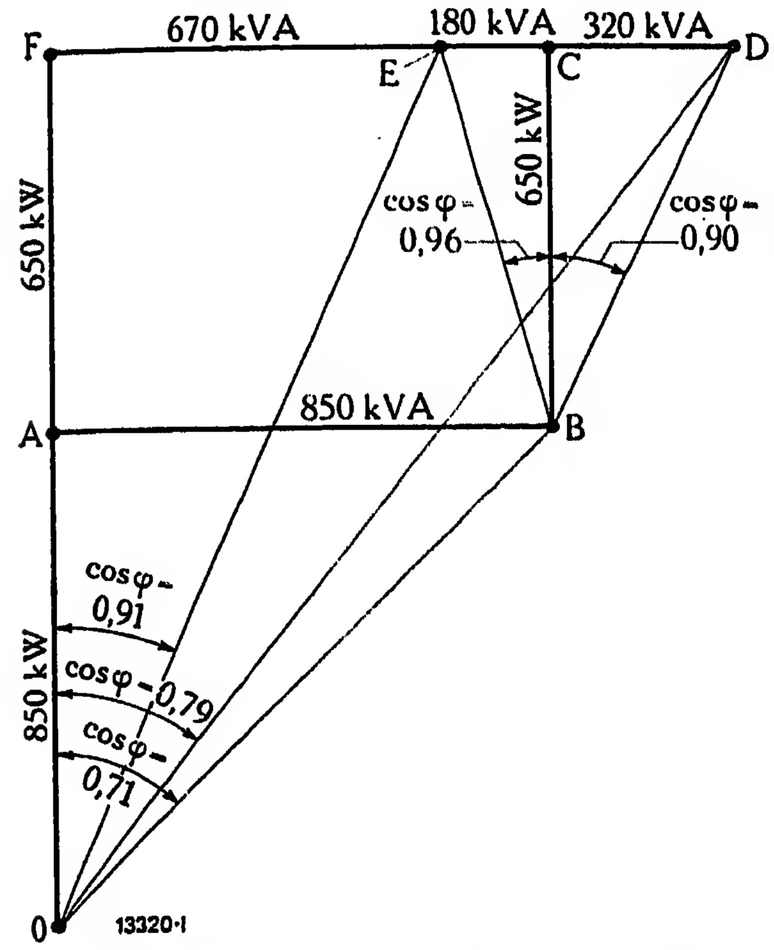

Fig. 1. — Vector diagram showing the watt and wattless input with the power input of the large motors equal to 650 kW.

The results are given by the vector diagrams Figs. 1 and 2; the watt components are in the vertical direction and the wattless components horizontal. Instead of the angles φ, the values of cos φ corresponding to the power factor are given in the diagrams. The total power input of the two main motors is 650 kW in Fig. 1, and 400 kW in Fig. 2. In both cases OA represents the watt component and AB the lagging wattless component absorbed by the smaller motors; BC the watt component, CD the lagging wattless component without a phase advancer, and CE the leading wattless component with phase advancers in the case of the two larger motors. The total power consumption in kW of the whole plant is OF, the wattless kVA input is FD with no phase advancer and FE when the two main motors are fitted with this device.

The saving effected by advancing the power factor depends naturally on the tariff.

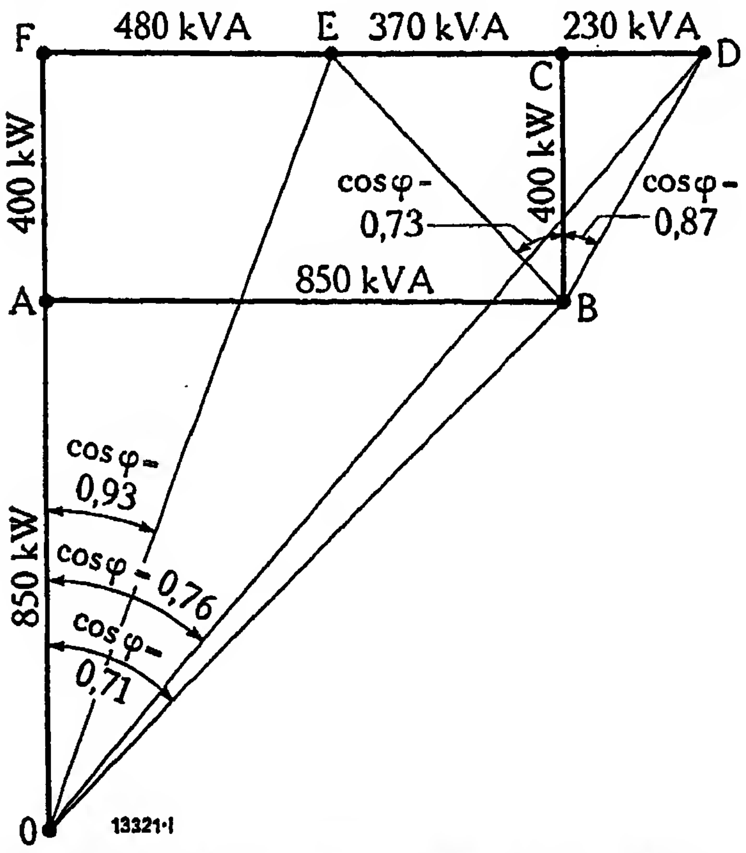

Fig. 2. — Vector diagram showing the watt and wattless input with the power input of the large motors equal to 400 kW.

With one of the variable tariff systems (Fig. 3), the ground rate is based on a value of cos $\varphi = 0{\cdot}8$. For cos $\varphi > 0{\cdot}8$ the price per unit is lowered, whereas, for cos $\varphi < 0{\cdot}8$ the price per unit is raised. The relation between the cost per unit and the power factor is shown by the curve — the price being given as a percentage of the price per unit when cos $\varphi = 0{\cdot}8$. By improving cos φ from 0·4 to 1·0, the cost of the kWh would be lowered from 167 % to 77 % of the ground rate. On the basis of a ground rate of 0·08 francs per kWh, the following prices per unit correspond to the values of the power factor obtained in the example just dealt with: —

with cos $\varphi = 0{\cdot}76$	1 kWh	costs	0·083 fr.
„ cos $\varphi = 0{\cdot}79$	1 kWh	„	0·081 fr.
„ cos $\varphi = 0{\cdot}91$	1 kWh	„	0·074 fr.
„ cos $\varphi = 0{\cdot}93$	1 kWh	„	0·073 fr.

Assuming 2400 working hours per year and a power consumption of 1500 kW, the cost of energy without a phase advancer (cos φ = 0·79) is

$$1500 \times 2400 \times 0{\cdot}081 = 292\,000 \text{ fr. per year.}$$

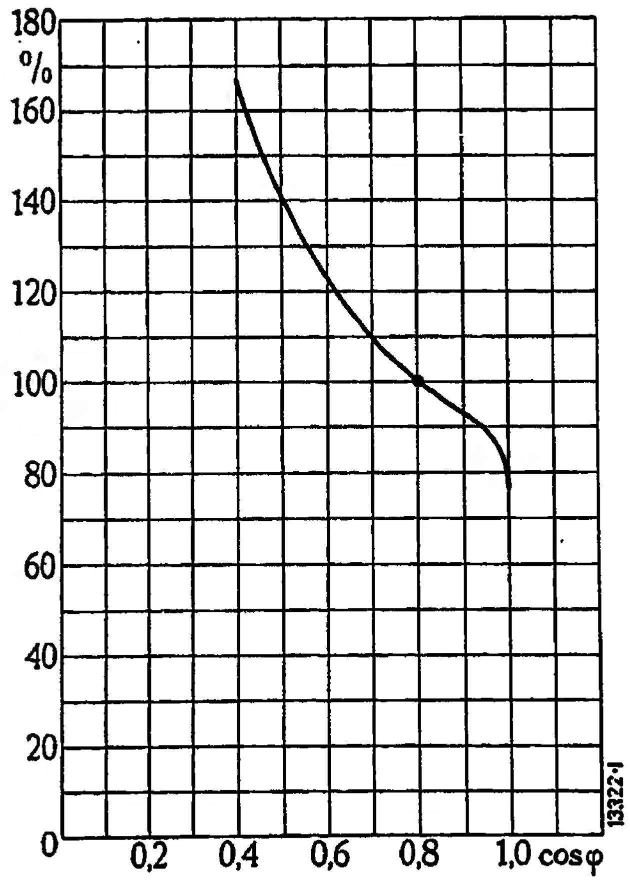

Fig. 3. — Curve giving the price per kWh as a function of the power factor, cos φ.

while with a phase advancer (cos $\varphi = 0{\cdot}91$) the cost is

$$1500 \times 2400 \times 0{\cdot}074 = 266\,000 \text{ fr. per year.}$$

The saving due to the use of phase advancers amounts to 26 000 fr. per year with

this tariff. No account has been taken here of the losses in the phase advancer, which must naturally be deducted. This question will be gone into more fully later on. If the power consumption is only 1250 kW and the working hours the same, the annual cost of the electrical energy is 249 000 and 219 000 fr. respectively, the values of the power factor being 0·76 and 0·93. In this case the saving amounts to 30 000 fr.

Another system consists in raising the price of the kWh by $a \times 0{\cdot}0004$ fr. when the power factor is $a \times 0{\cdot}01$ below a given value. As no advantages can be gained by raising the power factor above this value, consumers are not likely to exceed it. In order to make it worth while improving the power factor as much as in the foregoing example, this value should at least be equal to 0·93. In this case the saving due to the phase advancer would be:

(a) When the energy consumption is 1500 kW for 2400 hours per year and the power factor raised from 0·79 to 0·91:

$100\,(0{\cdot}91 - 0{\cdot}79)\;0{\cdot}0004 \times 1500 \times 2400 = 17\,300$ fr. per year.

(b) When the energy consumption is 1250 kW for 2400 hours per year and the power factor raised from 0·76 to 0·93:

$100\,(0{\cdot}93 - 0{\cdot}76)\;0{\cdot}0004 \times 1250 \times 2400 = 20400$ fr. per year.

On some other systems the tariff depends on the wattless kVAh consumption. In certain cases a charge equal to one-third of the price per kWh is made for each wattless kVAh consumed when the power factor of the entire plant becomes lower than 0·9. For power factors of 0·9 or higher, no charge is made for the wattless kVAh. In the forgoing example, the power factor compensation was unnecessarily high. Over-compensation of the main motors is, however, justified when the plant comprises so many motors with a low power factor that the resultant power factor of the plant is less than 0·9. With 2400 working hours per year the phase advancers will save $2 \times 250 \times 2400$ or $2 \times 300 \times 2400$ wattless kVAh per year for the loads of the main motors considered above. With energy at 0·08 fr. per kWh as before, the kVAh would cost $\frac{0{\cdot}08}{3}$ fr., so that an annual savin of 32 000 and 38 400 fr. respectively can be realised by employing phase advancers.

Still another system consists in fixing the ground rate for $\cos\varphi = 0{\cdot}71$. For this value of the power factor the watt component of the current is equal to the wattless component. With a higher power factor, i. e., $\cos\varphi > 0{\cdot}71$, when the wattless component of the current is smaller than the watt component, a rebate equal to 10 % of the cost per kWh is granted on the difference between the kWh consumption and the wattless kVAh consumption. When $\cos\varphi < 0{\cdot}71$, the wattless component is greater than the watt component, and a rate equal to 20 % of that charged per kWh has to be paid on this difference. In the example considered, 1 200 000 and 1 440 000 kVAh per year are saved for the two loads in question by installing phase advancers. With energy at 0·08 fr. per kWh, and a resultant power factor under 0·71, the saving obtained by phase advancers would be: $0{\cdot}2 \times 0{\cdot}08 \times 1{\cdot}2 \times 10^6 = 19\,200$ fr. per year and $0{\cdot}2 \times 0{\cdot}08 \times 1{\cdot}44 \times 10^6 = 23\,000$ fr. per year respectively.

For a power factor higher than 0·71 these values must be halved. With another tariff, the rebate allowed is 6 % and the extra charge 12 %, so that the advantages entailed by fitting a phase advancer would be represented by 60 % of the values just given.

In all these calculations no account has been taken of the losses due to the power factor correction.

As long as the power factor of the induction motor does not become leading, the stator losses are reduced on account of the smaller current; the rotor losses generally increase, but, as this augmentation is always less than the reduction of the stator losses, the total losses are decreased. This is especially the case with high-tension motors. The overall efficiency is slightly lowered, by about 0·5 to 1 %, on account of the losses in the phase advancer. If the power factor becomes leading, the motor losses may be increased by advancing the phase instead of being reduced. In the example considered, the conditions are unfavourable as the power factor of the motor is appreciably over corrected, and the adoption of a phase advancer increases the losses by about 6·5 kW at full load and by 13·5 kW at a load of 200 kW. In 2400 hours, 15 600 and 32 400 extra kWh are required when a phase advancer is fitted. The price per kWh could be taken as a function of the power factor from one of the tariffs already given, however, if an average value of 0·08 fr. per kWh is assumed, the

extra energy consumed would cost 1250 and 2590 frs. per year respectively. These additional values have to be subtracted from the differences which have been already calculated. The net annual saving obtained by using phase advancers varies according to the tariff and the load from 8350 to 35 810 fr. in the example considered. Only with the last tariff of all and with the most unfavourable load, would this gain drop to 4310 frs. The outlay involved by the phase-advancer plant, including the auxiliary costs, amounts at present to 25 000 fr., it would therefore take $^3/_4$ to 3 years to pay this off.

The kVA saving which can be attained with a given phase advancer depends on the characteristics of the induction motor to which it is fitted, and is inversely proportional to the full-load slip of the induction motor. Moreover, it is only possible to get the full benefit of a phase advancer with certain definite values of the rotor current and pressure of the induction motor. In the example considered, the slip of the induction motor at full load is very high (2·5 %), and also, the phase advancers are not loaded to their full extent. Therefore, with the same type of phase advancer and more favourable conditions it would be possible to more than double the kVA saving realised in the above example, and, even with the last tariff mentioned, the total outlay involved by installing the phase advancer would be paid off within a very short time.

As power-factor correction reduces the stator current, the losses in the distribution system between the electric meters and motors are smaller. In the example treated, no account has been taken of the corresponding saving, which can be quite considerable.

Moreover, the speed of the phase advancer was adjusted in such a way as to ensure an equally favourable correction at all loads. Naturally, with hand regulation this is only possible when the load does not often vary. Automatic regulation, although more favourable, complicates the plant. Without it, however, a phase advancer is worth adopting, as, even at partial loads of the main motor it is efficacious, although the full benefit is not obtained — at quarter load, for instance, it is often possible to raise the power factor to unity. No advantages are gained when the main motor is running idle. In a great many cases, however, this never occurs, as the no-load losses of the driven machines form an appreciable portion of the useful load.

Another advantage of the phase advancer, which cannot be expressed in figures, is that the overload capacity of the induction motor to which it is fitted is greatly increased. This often allows a smaller induction motor to be chosen than would have been the case if a phase advancer had not been employed.

It is not intended to make a comparison of the costs involved by fitting a phase advancer and those of other devices for improving the power factor, as the results depend to a great extent on the conditions assumed, and cannot therefore be generalised. Mention may be made of synchronous motors, of which two distinct types are now used, namely the synchronous motor (with salient poles) and the synchronous type of induction motor. The former is more suitable for supplying mechanical energy at the same time, than for raising the power factor alone. It is not suitable, however, for every kind of drive. If a synchronous motor running light is chosen for compensating the power factor of existing induction motors, account must be taken of the no-load losses of the synchronous motor when comparing it with the other methods of phase correction. With large motors these no-load losses are equal to about 5 % of their wattless kVA consumption, and are considerably greater with small motors. In the example considered, the losses due to a synchronous motor running light would amount to at least 25—30 kW, i. e., 18·5 and 16·5 kW more than if phase advancers had been fitted. This difference is further increased if the main motor has such a low power factor that a sufficient saving of wattless current can be ensured by raising the power factor to unity. In order to be able to compete with the phase advancer, the synchronous motor must be cheaper by an amount corresponding to the extra losses. Also with *synchronous induction motors*, the losses when running idle, and loaded, play an important part when comparing the costs. Care must be taken, when the excitation is not regulated, that the leading wattless kVA component on no load does not exceed the requirements of the plant.

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Published by BROWN, BOVERI & CO., BADEN (Switzerland). Printed by Kreis & Co., Basle.

OIL SWITCHES AND ACCESSORIES FOR PRESSURES UP TO 35000 VOLTS.

Decimal index 621.317.3.

Of all the apparatus required for the control of electric machinery, the switch is one of the most important, inasmuch as the safe working of the plant depends to a great extent on its reliability.

The knife and horn-type switches as used for smaller outputs and pressures are useless for the high pressures now adopted in modern plants. Their principal shortcoming is due to the liability of the arc formed when switching off to spread to the air surrounding the apparatus. Furthermore, not only did these switches have very unwieldy dimensions, but they also have a prejudicial influence on the machines and system on account of the formation of overpotentials when switching off.

Brown, Boveri & Co. was one of the first firms to manufacture oil switches, i. e., switches with break under oil instead of in air.

On account of the contacts being immersed in oil, the spark is immediately extinguished. With alternating current for which oil switches are mostly used, the circuit is interrupted approximately at the moment when the current curve passes zero, so that abnormal pressure rises are avoided. The great dielectric strength of oil enables these switches to be built smaller than air-break switches, so that they are more suitable for being embodied in switchboards. Moreover, hand and electric remote control can also be easily provided as well as automatic releases.

The Brown Boveri oil switch for pressures up to 35000 volts, together with its different types of control and accessories, forms the subject of the following description.

OIL SWITCHES.

Figs. 1 and 2 show the present design of a Brown Boveri oil switch. The insulation is such that the disruptive strength of the oil is greater than that of the air surrounding the insulators. Should a flashover occur, it would take place through the air,

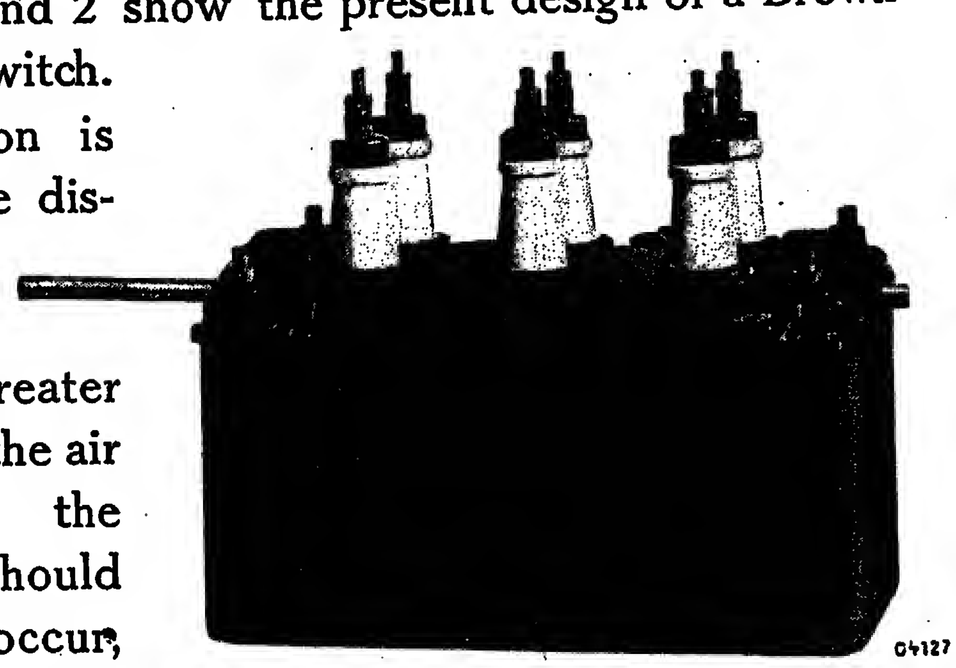


Fig. 1. — Triple-pole oil switch with front drive.

and not through the oil. Moreover, puncturing of the insulators perpendicular to the leading-in studs is impossible.

The whole of the switch mechanism, control gear and oil tank are suspended from the switch cover.

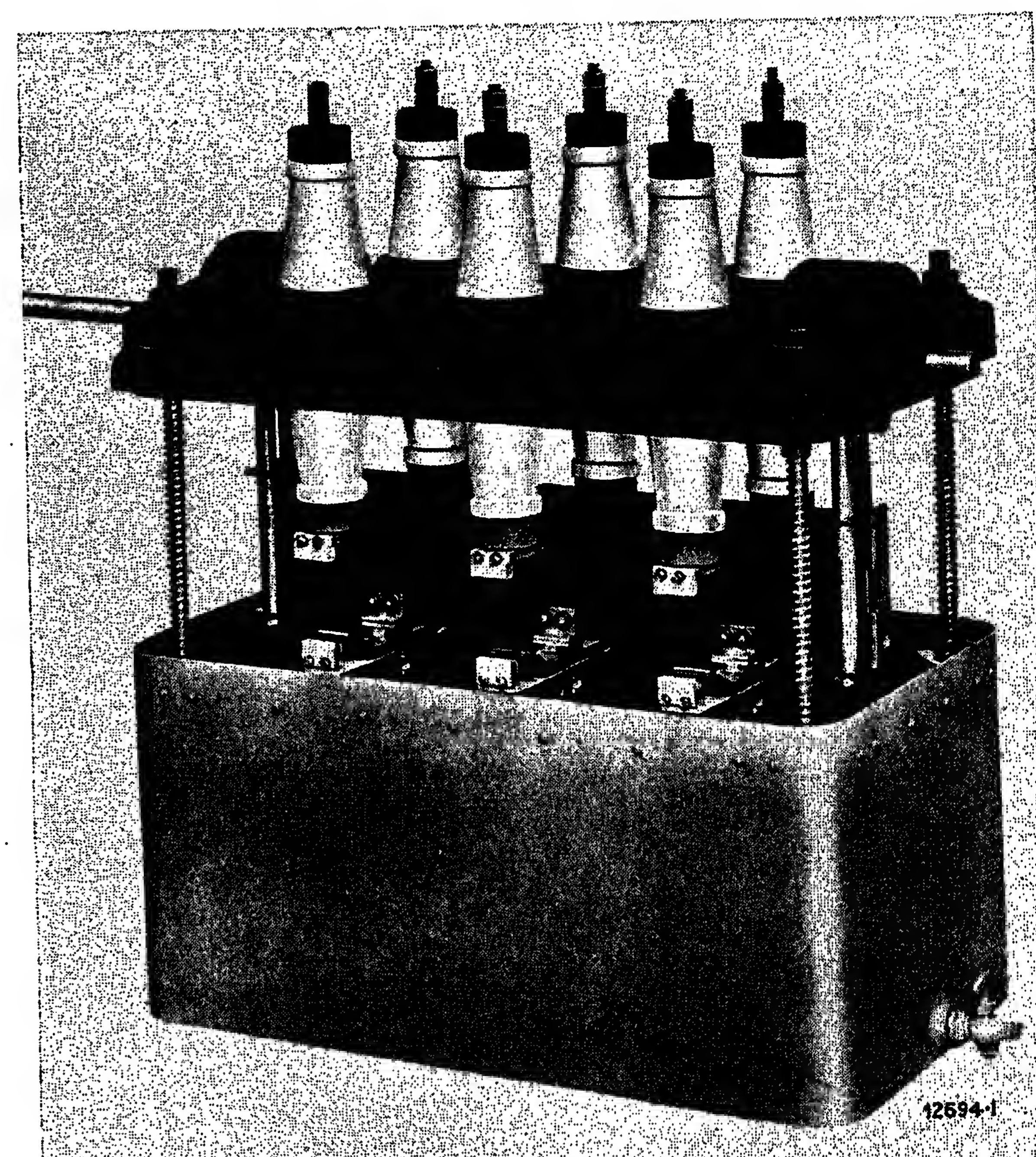


Fig. 2. — Triple-pole oil switch with oil tank lowered.

The terminal insulators have a smooth surface, so as to obviate dust deposits and facilitate cleaning. Those for smaller types are designed to withstand a working pressure of 12000 volts and cemented direct into the cover; larger types have the insulators fixed to flanges which are screwed to the cover, thus permitting quick replacement in case of damage. The stationary main contact pieces and the interchangeable sparking tips are fixed to the lower end of the leading-in studs. The movable contacts (Fig. 3) are carried by a plate made of insulating material of great dielectric as well as

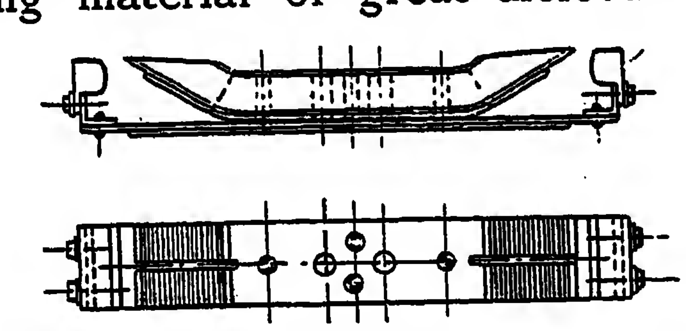


Fig. 3. — Main movable contacts with sparking tips.

mechanical strength, and likewise consist of main contacts with sparking tips. The former are laminated,

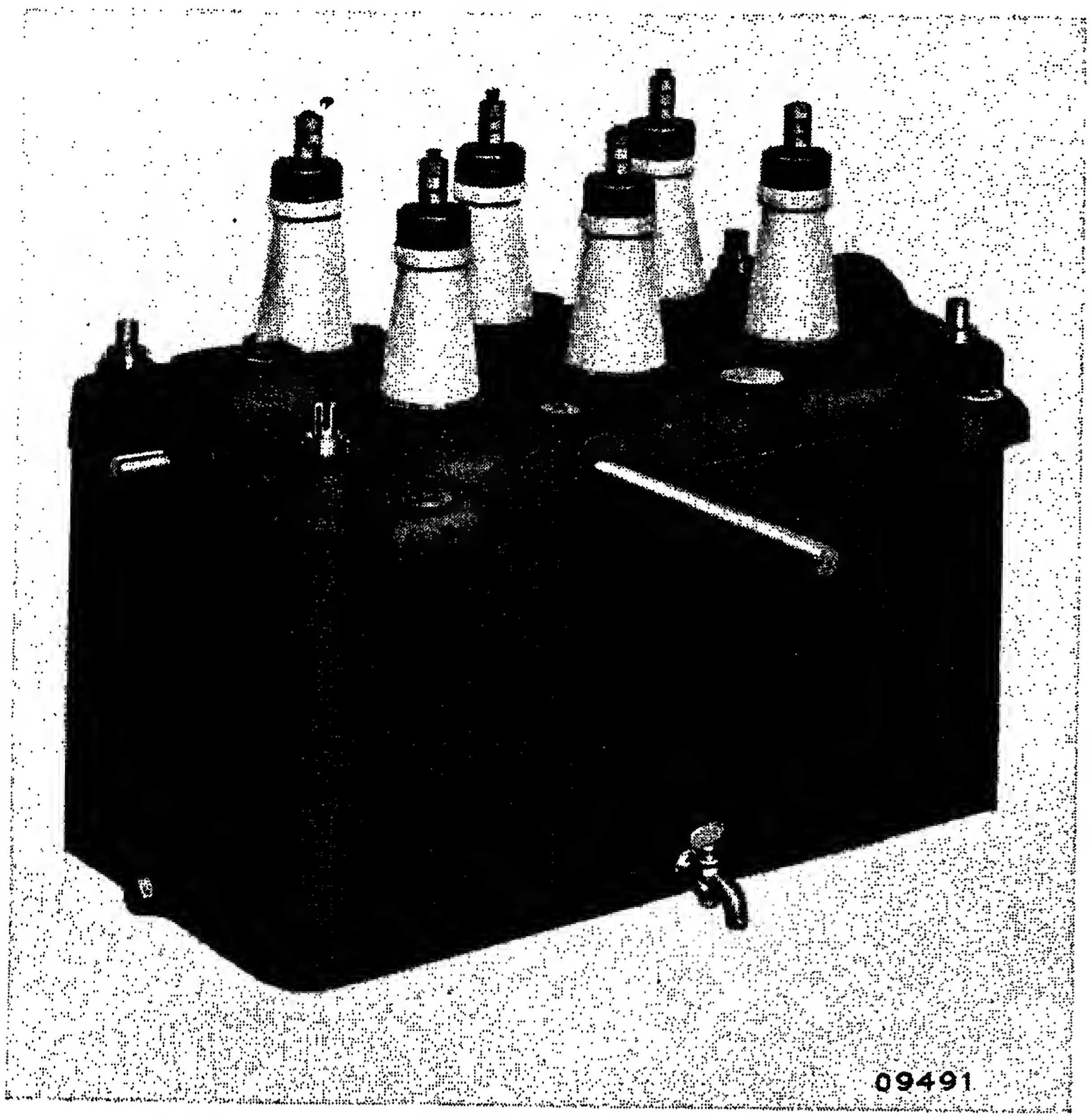


Fig. 4. — Triple-pole oil switch with side drive.

whereas the sparking tips are solid copper blocks. All contacts are liberally dimensioned to avoid burning in case of short circuits.

The switching mechanism has no parts liable to damage, and can therefore be used for high breaking speeds. These are attained by providing a strong spiral spring fixed to the spindle of the oil switch, and by the contacts themselves. Each phase is interrupted twice by a sufficiently large gap. In the off position, the movable insulating plate forms a separating partition between the contacts.

The oil tank is made of welded sheet iron. It is fixed to the cover of the switch by four threaded columns, and let down by hand from any one corner with a ratchet. Interruptions due to the oil tank falling, which occasionally occur with cable-suspended tanks, are therefore completely avoided. Holes with caps are provided in the cover for filling the tank with oil; for emptying it, the smaller type switches have an outlet with a screw plug, and the larger ones a drain cock.

The switches are arranged for front or for side drive (Figs. 1 and 4); one end of the spindle receives the operating handle or wheel, and the other the signal contact. The angle of rotation of the switch is 165° for all types, switching in being done by turning the wheel clockwise.

The oil switches are built both with two and with three poles for pressures up to 35 000 V and currents up to 3000 A. In Table I, which gives the test and breakdown pressures for different sizes of oil switches:

A designates the sparking gap from the cap of the terminal insulators to the cover of the oil switch;
B the distance from the live parts under oil to the oil tank, and
C the distance from the breaking point to the surface of the oil.

TABLE I.

Series type	Nominal pressure volts	Test pressure volts	Break-down pressure volts	Distances out of oil A mm	Distances in oil B mm	C mm
I	3000	10000	30000	75	40	90
II	6000	20000	40000	100	50	100
III	12000	30000	50000	125	60	120
IV	24000	50000	70000	180	90	180
V	35000	70000	80000	240	120	240

Account must be taken of the following factors when the most suitable size of an oil switch is determined: — the normal pressure of the power station, the normal working current or output, and the continuous short-circuit current of the machines which the apparatus is called upon to switch out. Table II has been compiled in order to assist in the choice of the correct type of oil switch for different conditions.

TABLE II.

Nominal pressure in volts	Lasting short-circuit current in amperes 1000	1500	2000	3000	4500	6000
3000	I	I	I	II	II	II
6000	II	II	II	III	III	III
12000	III	III	IV	IV	IV	—
24000	IV	V	V	—	—	—
35000	V	—	—	—	—	—

DRIVES.

According to local requirements, the switches are supplied with either:

1. Hand drive with tripping catch, for switching in and out by hand.
2. Hand drive with release, for switching in by hand and tripping automatically.
3. Remote control, for automatic operation.

If the switch is mounted close to the operator's stand, and if it is in a circuit which is fully protected by suitable devices, it can be fitted with simple hand control. These hand drives are provided with a catch (Fig. 5) which holds the switch in the "on" position, and gives a quick break on releasing. For switching out, the handwheel is turned counter-clockwise, until it releases a clutch which allows the movable contacts to fall freely. Every hand drive is fitted with an indicating device showing the direction for operating and the position of the switch.

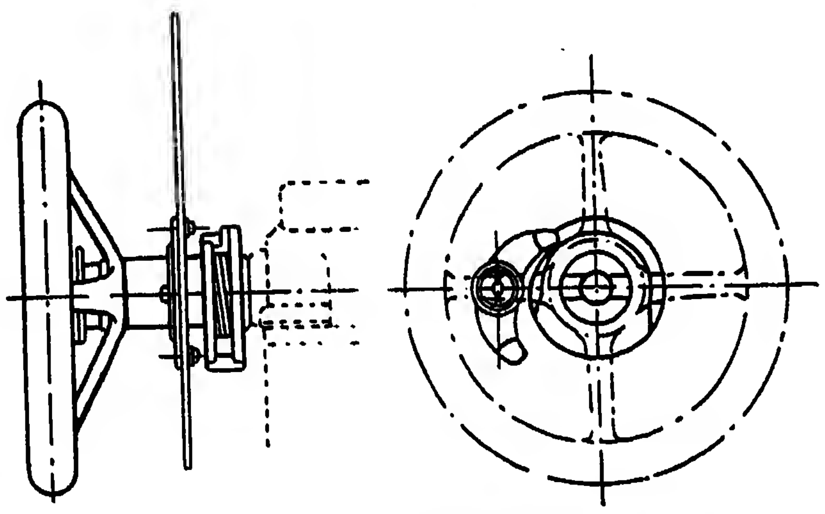


Fig. 5. — Handwheel with catch.

In plants where overloads are frequent, oil switches are always provided with automatic overload releases. The release can be operated by an overload time-limit relay in conjunction with a tripping magnet which causes the switch to come out either when energised (closed circuit) or when under no pressure (open circuit), by a reverse-power relay or by a direct-acting series time-limit relay mounted on the switch. Instead of a catch, these drives have a free-return clutch, which enables the switch to be tripped even when the handwheel is held in the "on" position.

The free-return clutch (Fig. 6) comprises the discs (b), fixed to the spindle (a) by pins, between the former are the pawls (c) and (d), which pivot about the pins (e) and (f) respectively. These pawls are made to engage together by means of springs (g) and (h). On the spindle (a) is the loose driving disc (k), which, together with the segment (i), is connected to the hand or chain wheel. In order to switch in, the disc (k) with the segment (i) is turned clockwise, and takes with it the pawls (c) and (d), as well as the spindle (a), until the pawl (c) catches the pawl (l). The interlocked pawls (c) and (d) have to be released to trip the switch. Once the pawl (c) is free, the spring (h) causes it to swing round, and it no longer engages with the pawl (l), so that the switch opens. The driving disc (k), which is kept in the "on" position by the pin (r), must be brought back to the "off" position by hand. When switching out by hand, the

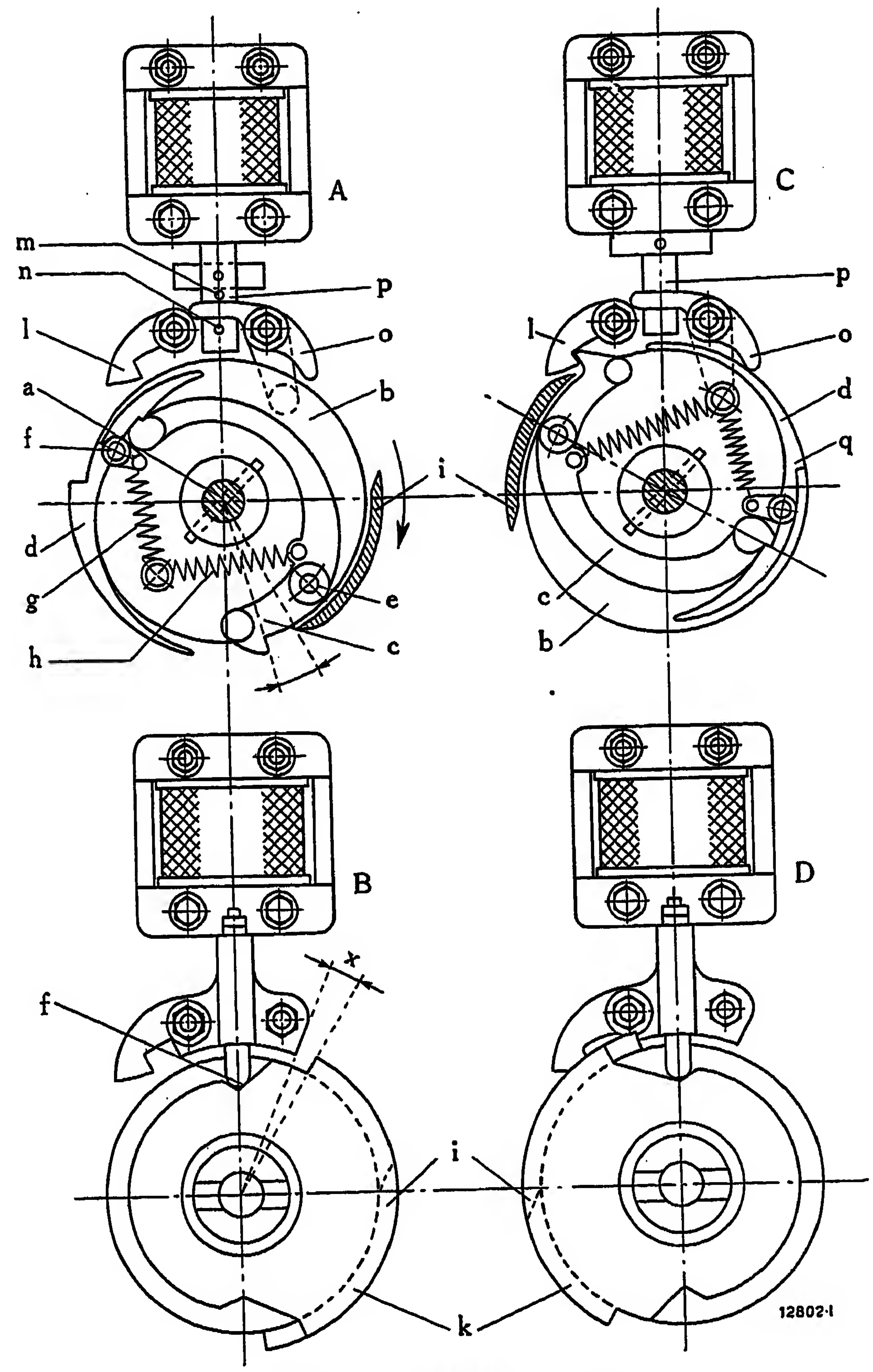


Fig. 6. — Free-return clutch.
A, B: "off" position. C, D: "on" position.

driving disc (k) is turned counter-clockwise, so that the segment (i) presses on the pawl (d), thus disengaging the pawls (c) and (d), and consequently the spindle of the switch.

The free-return clutch is the same for the different kinds of drives used for these switches.

The principle classes of drive employed are the following: —

Hand drives.

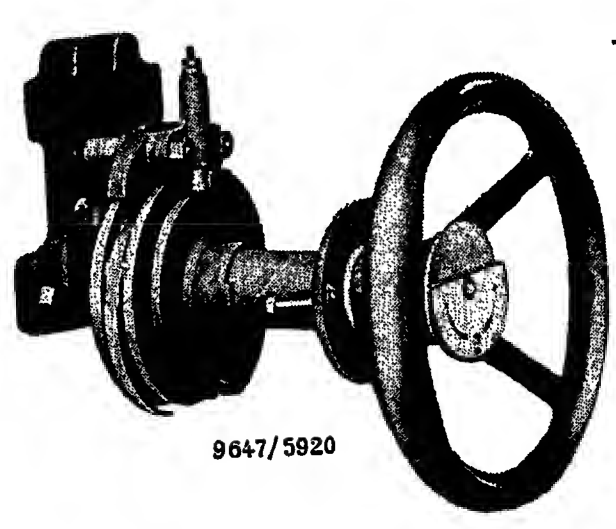


Fig. 7. — Hand drive, Type F 4a.

The commonest designs of hand drive employed are: Type *F 4 a, without* (Fig. 7) and *with* (Fig. 8) magnetic release, where the switch and free-return clutch are mounted behind the switchboard; Type *F 4 b, without* (Fig. 9) and

with (Fig. 10) magnetic release, for remote control; and finally Type *F6* with magnetic release (Fig. 11) for front-of-board switches. All drives can be fitted with auxiliary contacts for signal lamps (Fig. 12) or with a bell for indicating the position of the switch and its working to the attendant.

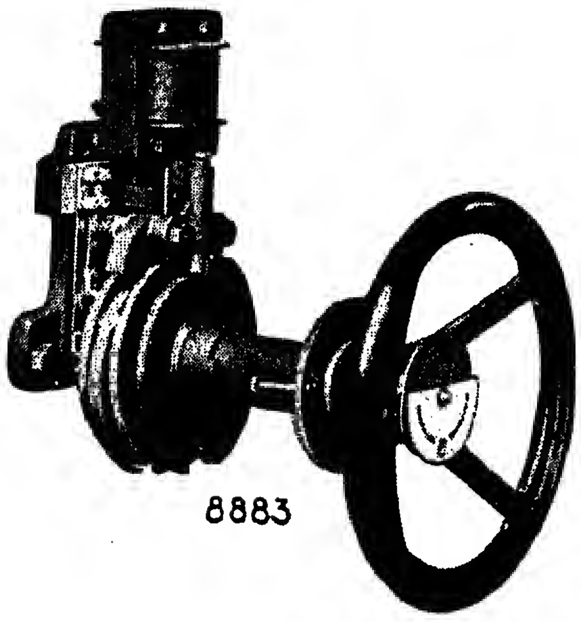


Fig. 8. — Hand drive, Type F 4a, with magnetic release.

The closed-circuit release (Fig. 13) works in the following manner: — The armature (p) of the tripping magnet is attracted, and the lever (o) lifted by the pin (n) presses on the pawl (d), thus tripping the switch. The *open-circuit* release (Fig. 14) acts as follows: — The armature (p) when falling, due to the magnet being de-energised, presses directly on the pawl (d). With a *direct-acting*

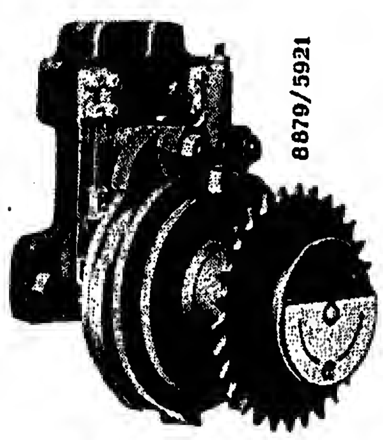


Fig. 9. — Hand drive, Type F 4b.

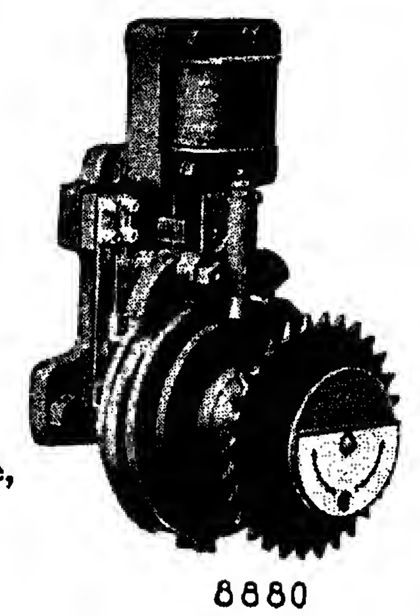


Fig. 10. — Hand drive, Type F 4b, with magnetic release.

series time-limit relay (Figs. 15 and 16), connecting rods trip the pawl (d) by means of the lever (o).

Remote control.

Mechanical remote control. If the handwheel has to be placed above or below the switch, at some distance from it, remote control is used (Fig. 17).

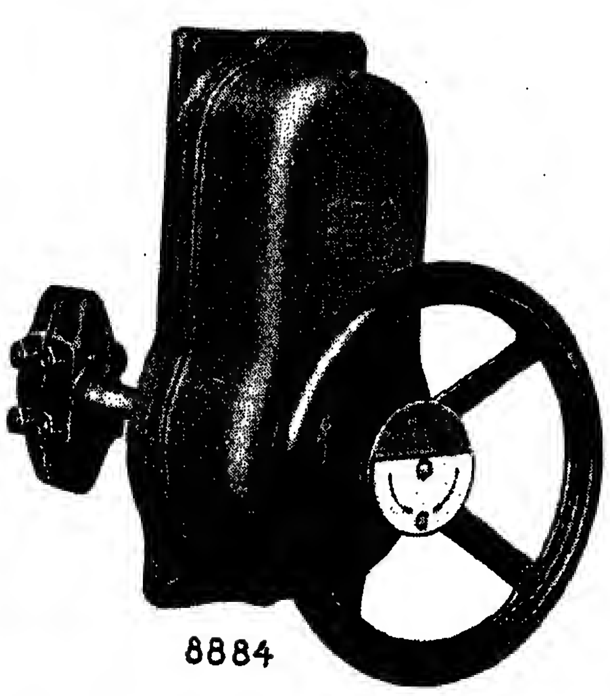


Fig. 11. — Hand drive, Type F 6, with magnetic release.

Instead of the handwheel being fixed directly on the spindle of the switch, a chain drive is adopted, with intermediate shafting if necessary. This kind of drive is only recommended for short distances, since long shafts and chains render control difficult.

Electric remote control. When the switch has to be erected at a considerable distance from the operating platform, as is generally the case in large power stations, electric remote control is used rather than hand drives, since it allows the control of all switches from one point, permits of a good overall

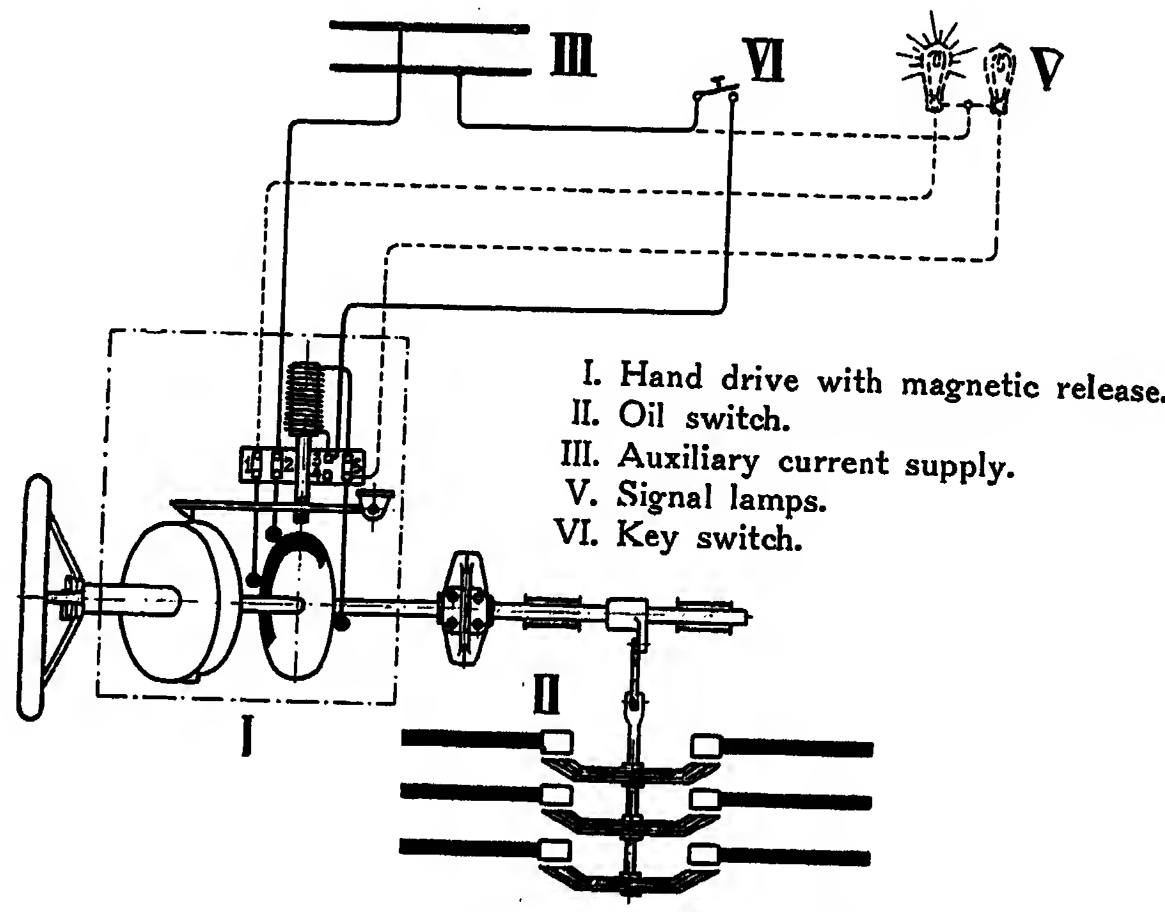


Fig. 12. — Hand drive with magnetic release.

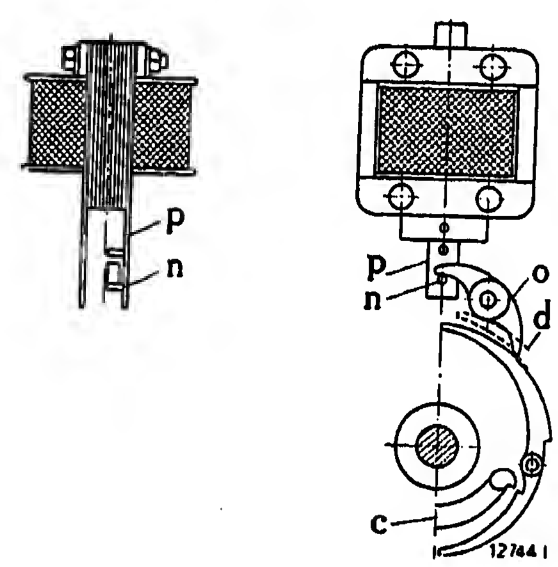


Fig. 13. — Closed-circuit release.

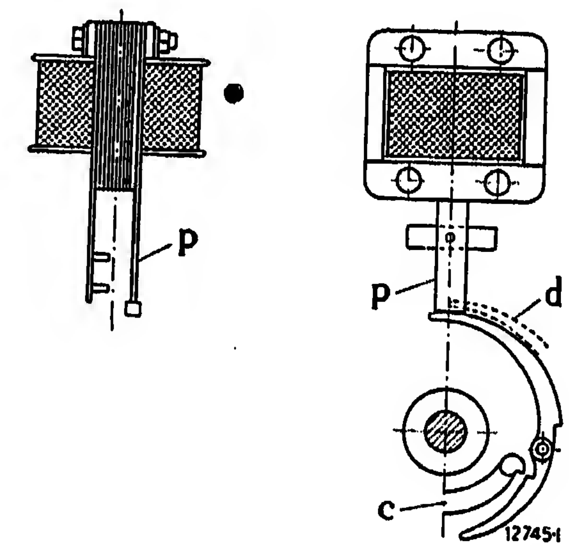


Fig. 14. — Open-circuit release.

arrangement of the plant, and reduces the attendance charges. Furthermore, paralleling, which is often difficult with mechanical remote control, can be done in a surer manner.

According the size of the switches and the power required to work them, as well as to the kind of current available, motor or magnetic operation is used.

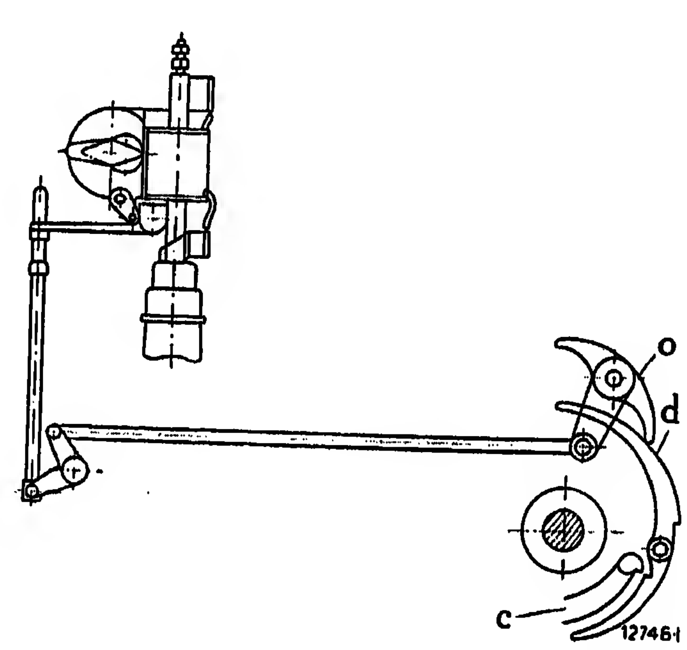


Fig. 15. — Release by direct-acting series time-limit relay.

(a) Magnet remote control (Figs. 18 and 19). Switching in is done by an iron-clad solenoid with movable core. The straight movement of the latter is changed to a rotary one by a rack and pinion.

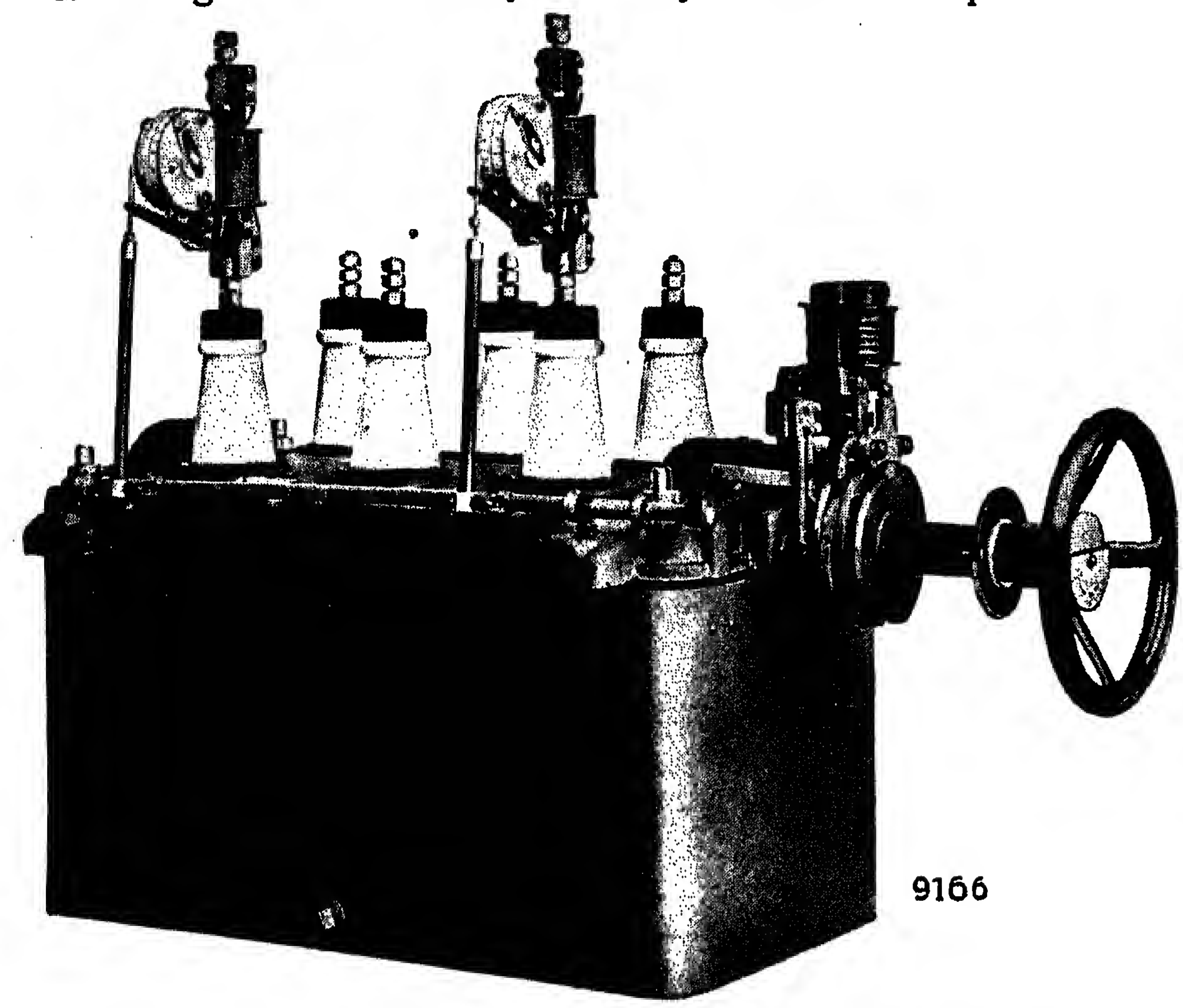


Fig. 16. — Triple-pole relay with series time-limit relay on two phases and no-volt release.

For switching out, a handwheel with magnetic release, which is built on the casing of the solenoid, is provided. Contacts with quick break open the solenoid circuit when the core reaches the top position, i. e. as soon as the switch is closed, so that the magnet is only energised for a short time. The indicator showing the position of the switch is operated by contacts on the spindle of the handwheel.

All connections are taken through the cable box at the bottom of the casing to a small terminal board which is easily accessible after removing a cover at the side. The magnet control device and the oil switch are connected by a universal coupling. According to the type, magnet controls can develop torques of 800—2500 kg cm. They can only be worked by direct current. The switch can also be operated by hand, using the handwheel with indicating device.

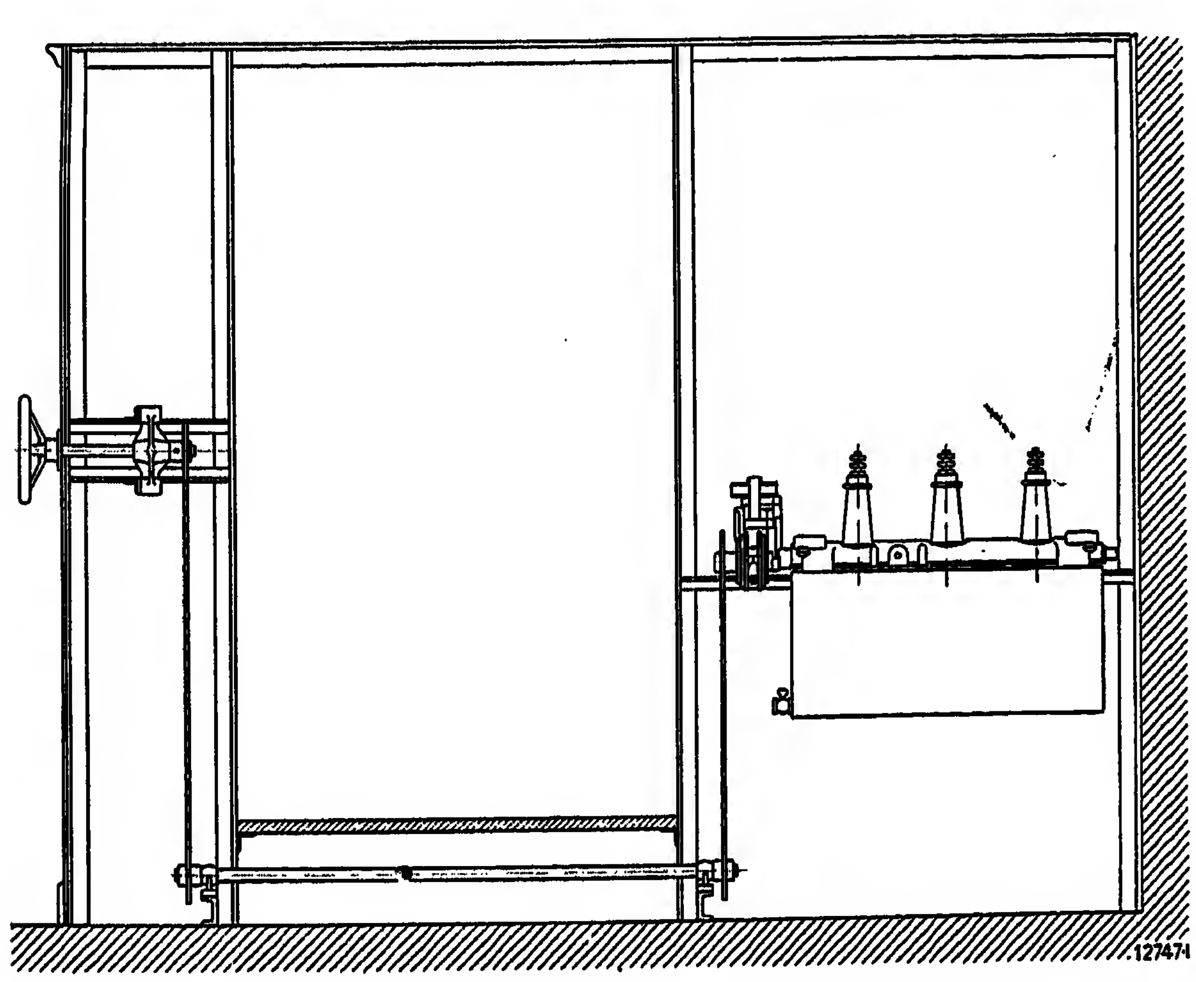


Fig. 17. — Mechanical remote control.

(b) Motor remote control (Figs. 20 and 21). Instead of a switching magnet, a commutator motor is used in this case. Gearing and friction coupling transmit its movement to the spindle of the oil switch. As soon as the switch is closed, the auxiliary circuit is opened by contacts with quick break. When the switch has been tripped, the motor brings the operating gear automatically to the switching-in position again. As before, a handwheel with magnetic release, mounted in a common casing with the motor and gearing is provided for switching off. The indicator showing the position of the switch and that of the mechanical drive of the switch spindle are the same as with magnet control. Motor remote control can be used with direct current or single-phase current for torques up to 2500 kg cm.

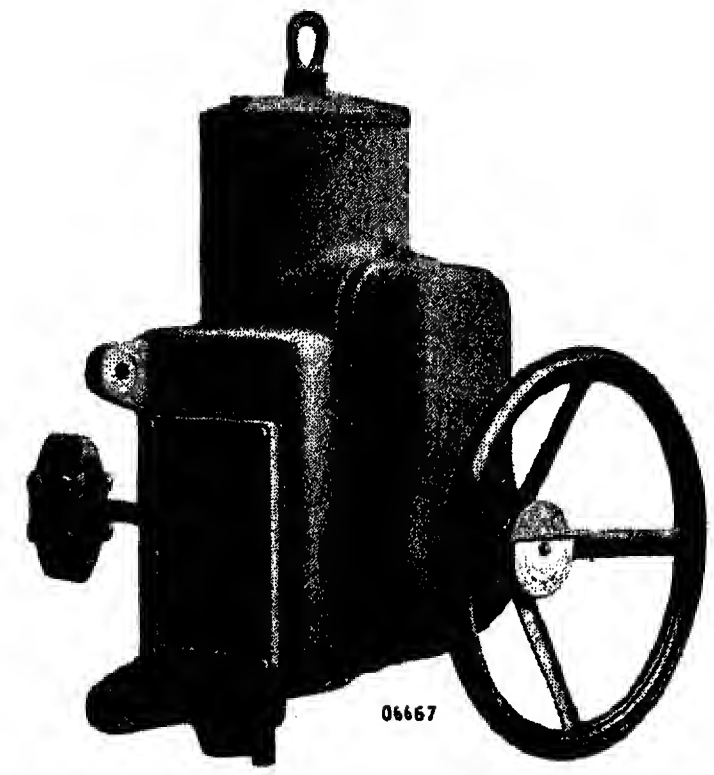


Fig. 18. — Magnet remote control, Type A.

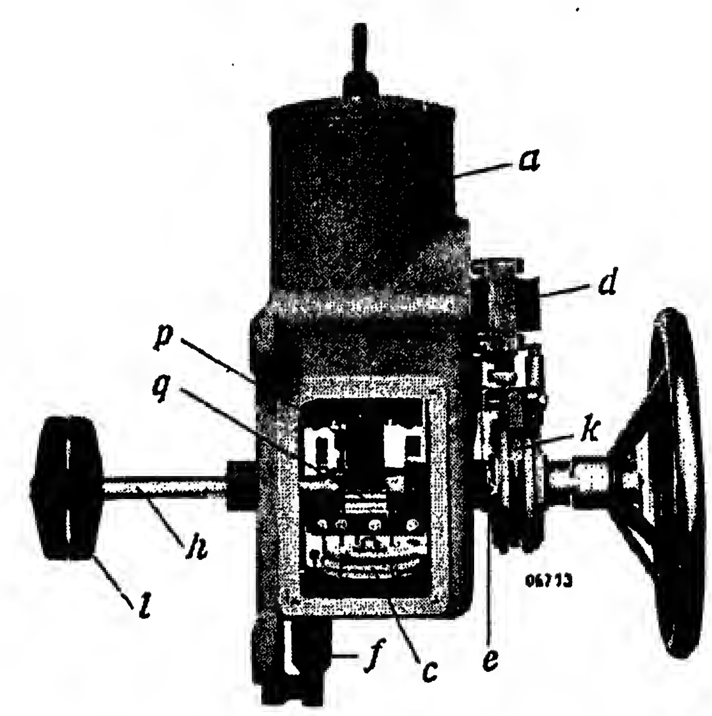


Fig. 19. — Magnet remote control, Type A, with side and protecting covers removed.

a. Magnet casing.
c. Damping resistance.
d. Releasing magnet.
e. Contact device.
f. Cable box.
h. Driving spindle.
k. Free-return clutch.
l. Universal coupling.
p. Toothed segment.
q. Rack.

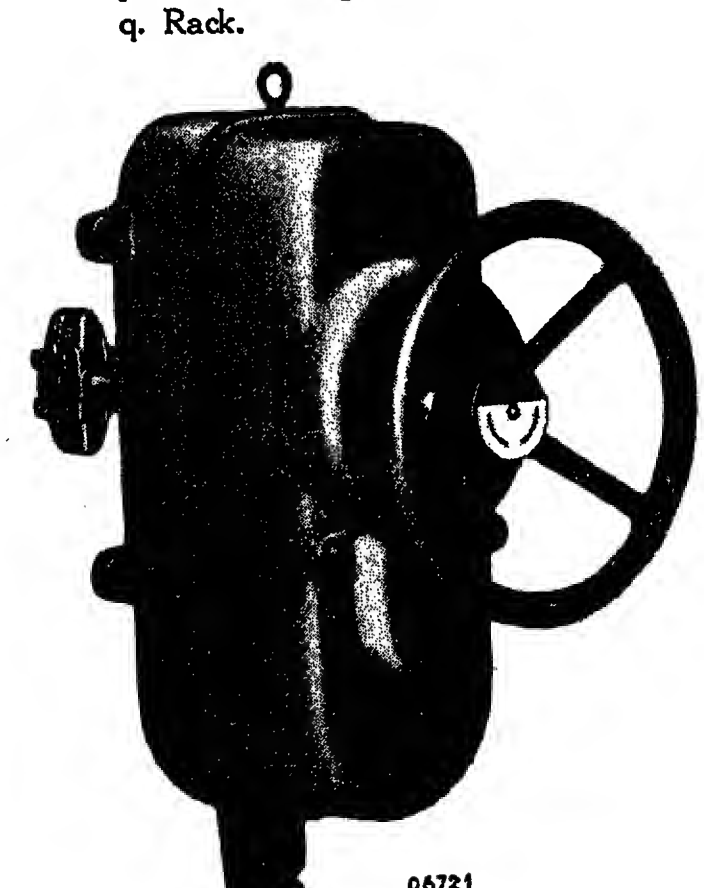


Fig. 20. — Motor remote control, Type N 4.

AUXILIARY APPARATUS.

To trip oil switches with magnetic release and to operate those with electric remote control from any required point, auxiliary switches are used, which are connected in the circuit of the magnetic release with hand drives, or in the operating circuit with electric remote control.

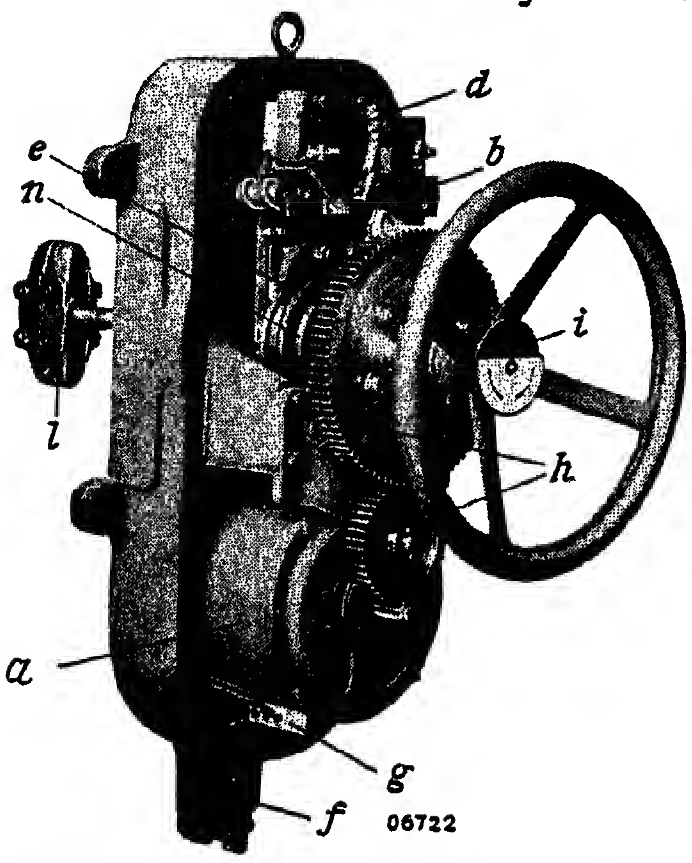


Fig. 21. — Motor remote control, Type N 4, with cover removed.

a. Commutator motor.
b. Switching contact.
c. Magnet operated by e.
e. Contact device.
f. Cable box.
g. Terminal board.
h. Friction coupling.
i. Indicator.
l. Universal coupling.
n. Free-return clutch.

If this circuit is permanently under pressure, as for instance with the open-circuit release, the tripping magnet opens the switch by opening the circuit; whereas, when the circuit is only under pressure intermittently, as with the closed-circuit release, the magnet operates by closing the circuit.

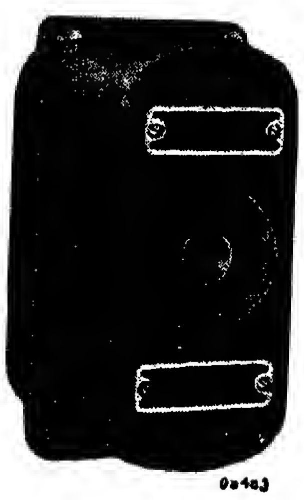


Fig. 22. — Push-button, Type A, with projecting casing.

As the majority of oil switches are at some distance from the operating platform, indicators for showing the sequence of switching operations carried out are necessary.

Pushbuttons and contact-makers serve to operate the auxiliary circuit; contacts and signal lamps being used as indicators.

The pushbuttons are employed for tripping hand-controlled switches with magnetic releases; they have spring return and can be adapted either for opening or for closing a circuit. Two types are built, namely: pushbuttons with projecting casing (Fig. 22) and the flush type (Fig. 23).

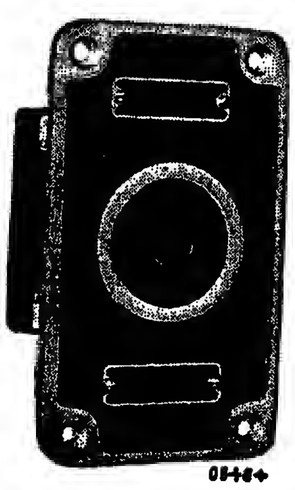


Fig. 23. — Push-button, Type B, with flush casing.

The contact-maker (Fig. 24) is used for closing or opening oil switches with electric remote control from the operating platform. It is fitted with a locking coil, which ensures complete closing of the main switch, even if contact is only made momentarily.

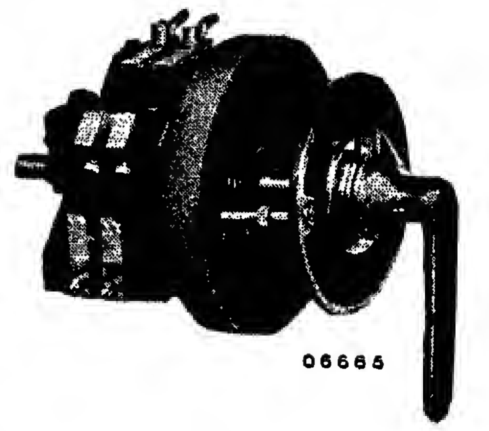


Fig. 24. — Contact maker, Type C 2.

A free-return clutch between the handle and the contact drum brings the latter back to the "off" position after it has made contact, and so prevents the actuating gear of remote-controlled switches coming into

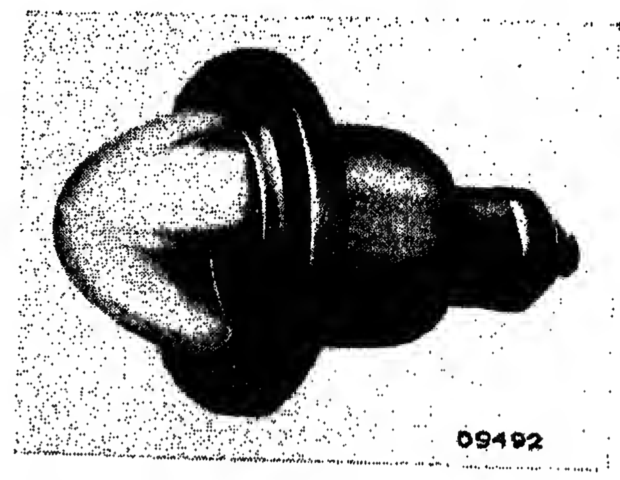


Fig. 25. — Signal lamp, Type S 2.

action and tripping repeatedly when closed on an excessive overload or a short circuit. A movable

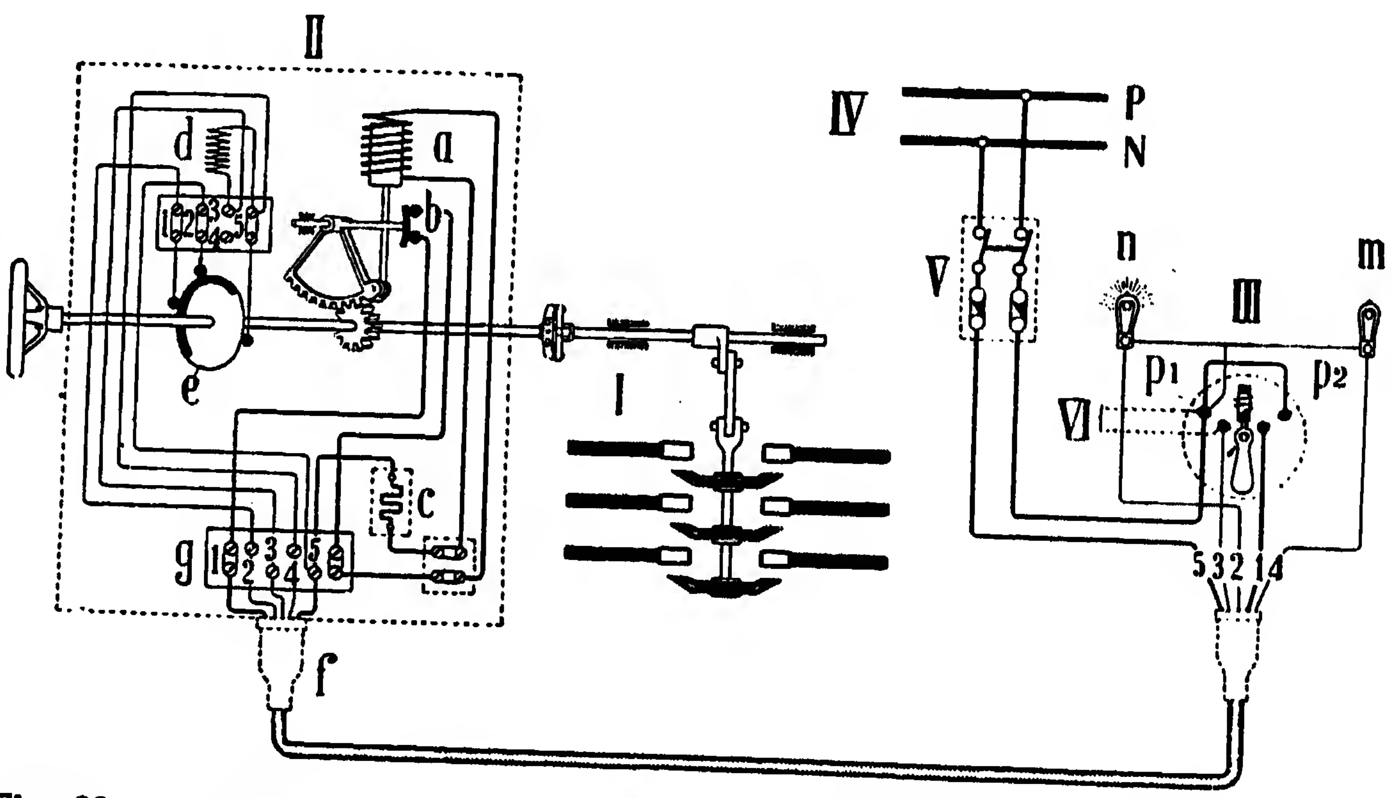
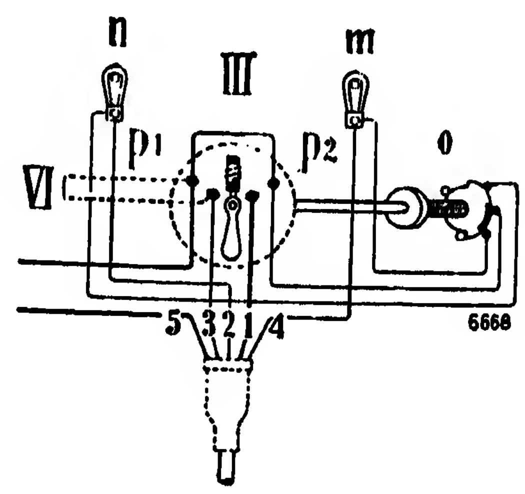


Fig. 28. — Diagram of connections of an oil switch with direct-current magnet remote control.

I. Oil switch.
II. Magnet remote control with:
 a. Switching-in magnet.
 b. Switching contact for a.
 c. Damping resistance for a.
 d. Releasing magnet.
 e. Contact device for d and the signal lamps.
 f. Cable box.
 g. Terminal board.
III. Contact-maker with locking coil and handle.
 m. Signal lamp "on".
 n. Signal lamp "off".
 o. Lamp change-over switch.
 p_1. "Off" position of o.
 p_2. "On" position of o.



IV. Auxiliary current supply.
V. Switch.
VI. Connections to relays.

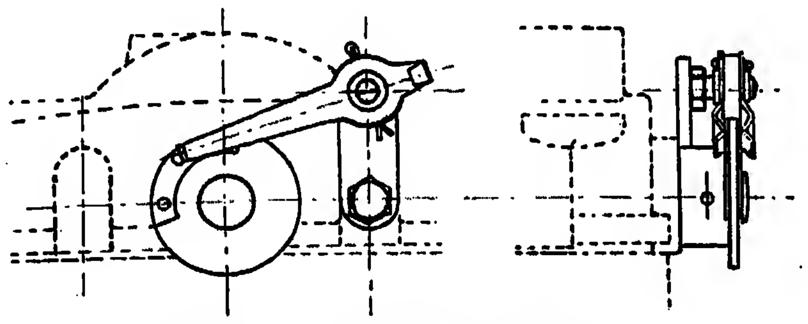


Fig. 26. — Switch contact.

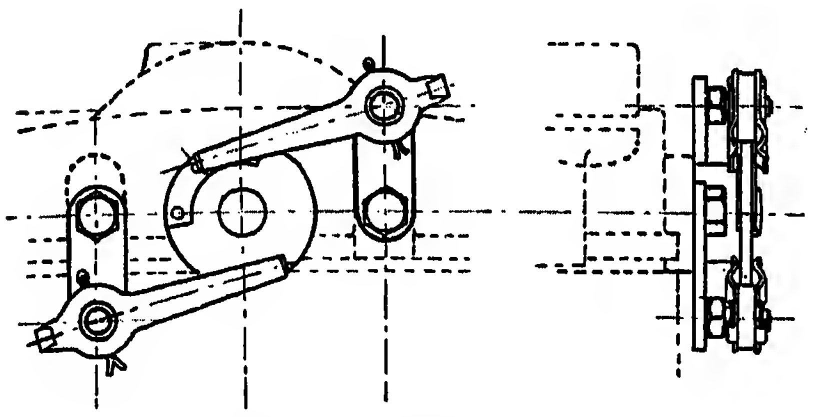


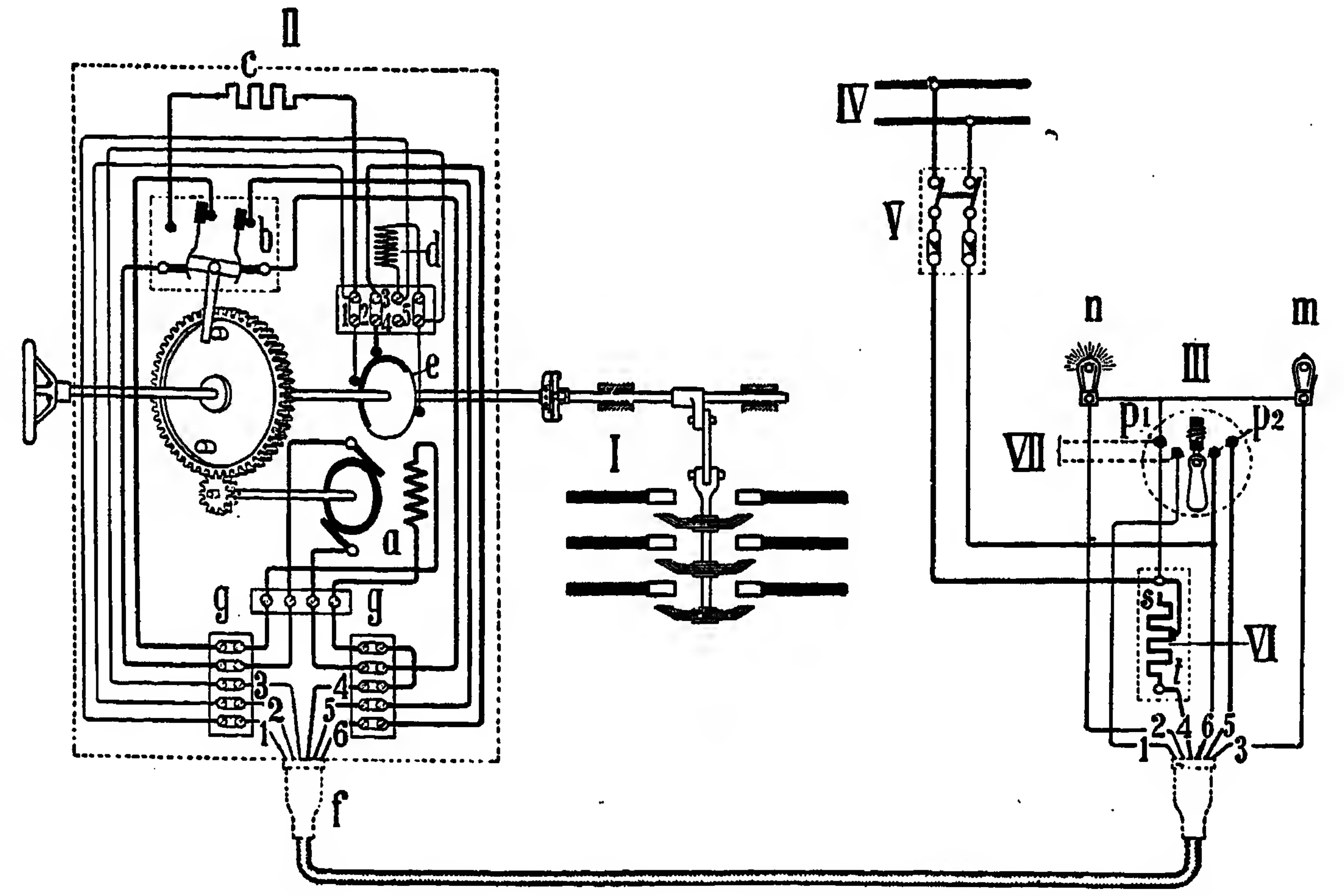
Fig. 27. — Change-over switch contact.

idle indicator, pushed by the handle, shows the last switching operation carried out.

The completed movement of the main switch is recorded by *signal lamps* (Fig. 25), switched in and out by contacts, which are positively driven by the remote control gear. Should it be desired to avoid having the lamps in circuit continuously, the contact-maker can be supplied with a special signal change-over switch, that causes the lamps only to remain lighted until the contact-maker has returned to its neutral position.

If other contacts are required besides those for the signal lamps, special switch contacts are provided on the back end of the spindle of the oil switch.

Fig. 28 shows a typical diagram of connections for an oil switch with magnet remote control, and Fig. 29 is the corresponding diagram with motor remote control.



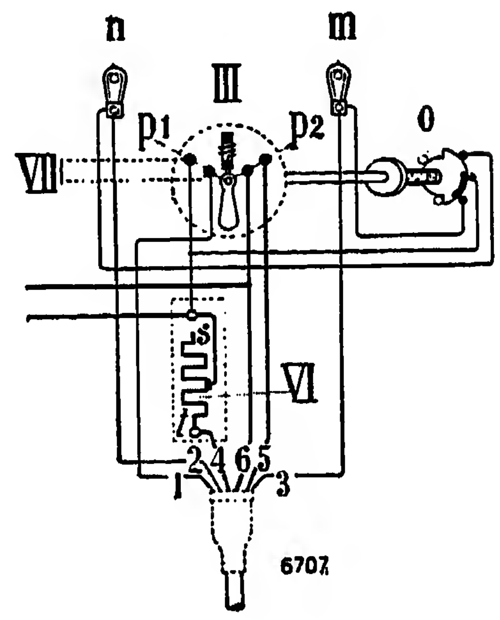


Fig. 29. — Diagram of connections of an oil switch with direct or alternating-current motor remote control.

I. Oil switch.
II. Motor remote control with:
- a. Switching-in motor.
- b. Change-over switch.
- c. Resistance for when motor returns to switching-in position.
- d. Releasing magnet.
- e. Contact device for the returning of the motor, the releasing magnet and signal lamps.
- f. Cable box.
- g. Terminal board.

III. Contact-maker with locking coil and handle.
- m. Signal lamp "on".
- n. Signal lamp "off".
- o. Lamp change-over switch.
- p_1. "Off" position of o.
- p_2. "On" position of o.

IV. Auxiliary current supply.
V. Switch.
VI. Switching-in resistances. s, t. Terminals.
VII. Connections to relays.

OIL CIRCUIT BREAKERS OF LARGE RUPTURING CAPACITY

BROWN, BOVERI & CO.
BADEN (SWITZERLAND)

782 E

May, 1923
(2044)

CONTENTS.

OIL CIRCUIT BREAKERS OF LARGE RUPTURING CAPACITY.

Decimal index 621. 317. 35.

1. GENERAL.

OIL circuit breakers serve to disconnect individual parts of a system while current is flowing either under regular working conditions, on overload, or in the event of a short circuit. The duty in the last-mentioned case is by far the most severe that a breaker is called upon to meet, not only as the short-circuit current is many times greater than the normal full-load current, but also because there is then a phase displacement of nearly 90^0 between current and pressure.

The rupturing process is extremely complicated, and especially the temperatures and pressures in the arc itself and in its immediate neighbourhood cannot be determined by direct measurement. Consequently, it is not possible to calculate the physical conditions governing the length and spreading of the arc, — that is to say, the space it requires, — and the effect it has on its immediate surroundings. The design of switches and circuit breakers immersed in oil is, for this reason, still based entirely on empirical data which are obtained from tests and experience.

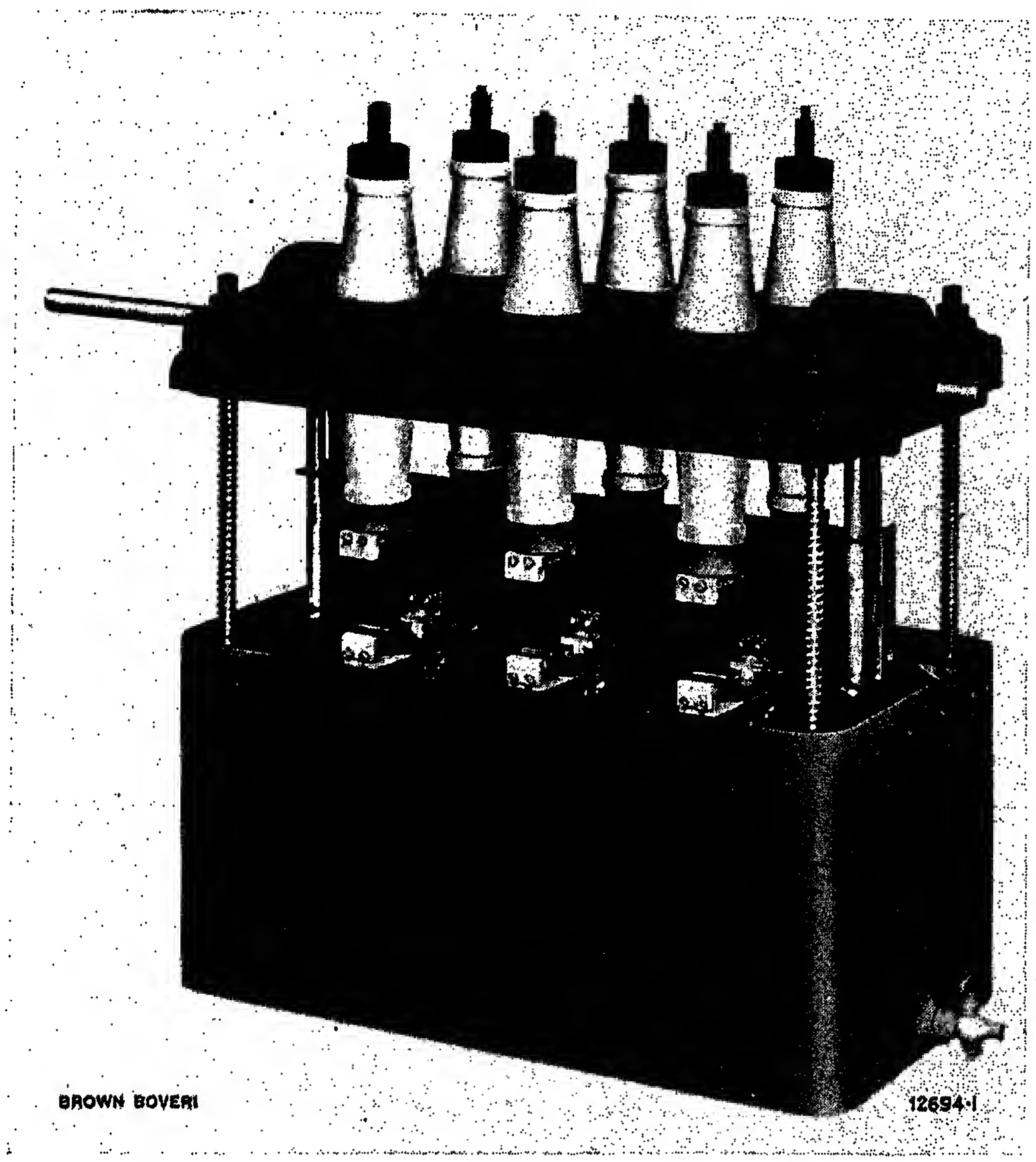


Fig. 1.— Triple-pole oil circuit breaker, Type A 8/3, 12'000 V, 200 A, with tank lowered.

Since, in order to test oil circuit breakers of large size properly, a greater amount of energy is needed for the short-circuit test than is ordinarily available, it is not surprising that very little information can be found in the technical literature regarding current-breaking tests on large switches. Among the few articles published may be mentioned those of Biermanns, Schrottke and Dr. Bruno Bauer. The results of the systematic tests carried out by the last-named investigator are to be found in the Bulletin of the Schweizerischer Elektrotechnischer Verein, 1915-7; they deal, however, only with relatively small powers.

It is evident that reliable information regarding oil circuit breakers is very necessary, as a breaker that is incorrectly designed or unsuitably chosen for given requirements can be a source of danger to the whole plant and to the attendants. On this account, all tests carried out methodically to determine the rupturing capacity of breakers for large powers are of very real interest. In section 7 of this article some such tests made by Brown, Boveri & Co. are described, while in section 4 comparative tests with smaller powers are dealt with.

The experience gained in actual practice is also a most important point. Brown, Boveri & Co. recognise this by keeping in constant touch with large power supply companies so as to obtain information at first hand. When a disturbance occurs, the cause and extent of it are examined immediately on the spot itself. In the case of a breakdown due to a short circuit, the load at the moment the disturbance took place is ascertained, this being done with the help of special impedance maps prepared for the large supply systems of Switzerland. The

experience gained is recorded in a suitable statistical form, which, on the one hand, enables sources of error to be easily seen and eliminated, and, on the other, permits the conditions to be determined under which the various types of circuit breakers can be relied upon to operate satisfactorily.

2. THE REQUIREMENTS AN OIL CIRCUIT BREAKER HAS TO FULFIL.

(a) Heating.

The heating of the oil, and of the various parts of the circuit breaker, must not exceed a certain limit when the full-load current flows continuously. Breakers for large currents must therefore be provided with accurately-made main contacts with ample contact surface and a sufficiently high contact pressure, while the sectional area of all current-carrying parts must also be liberal. In the case of relatively small currents — up to about 500 A — the finish of the contact surfaces is not important, as tests and experience have shown, but a good contact pressure is necessary. Even with contacts which had been so badly burned that they only touched at a few points, no excessive heating was observed. Consequently, there is no necessity to fit special main contact brushes to switches for such currents. The sparking tips at which the arc is broken can be dimensioned without considering the contact resistance. In any case, they will only touch at one point once they have been burned. These contacts should always be liberally designed so as to allow for a good deal of burning away. They heating of the breaker due to the arc formed when opening the circuit is never of any great consequence.

(b) Insulation.

The strength of the insulation between opposite poles, and between each pole and earth, must be roughly as great as that in other parts of the plant. Special care must be given to the insulation between parts belonging to the same phase which are separate when the breaker is out; they should not be connected by insulating pieces of wood, moulded paper or such material. When the breaker is open, nothing but oil should lie between the two contacts which come together when it is closed. Where solid insulating material is employed, there is the chance of a creepage path being formed by a deposit on it, or dampness may make it become a conductor to a certain extent. This could be a source of danger for men working on a line supposed

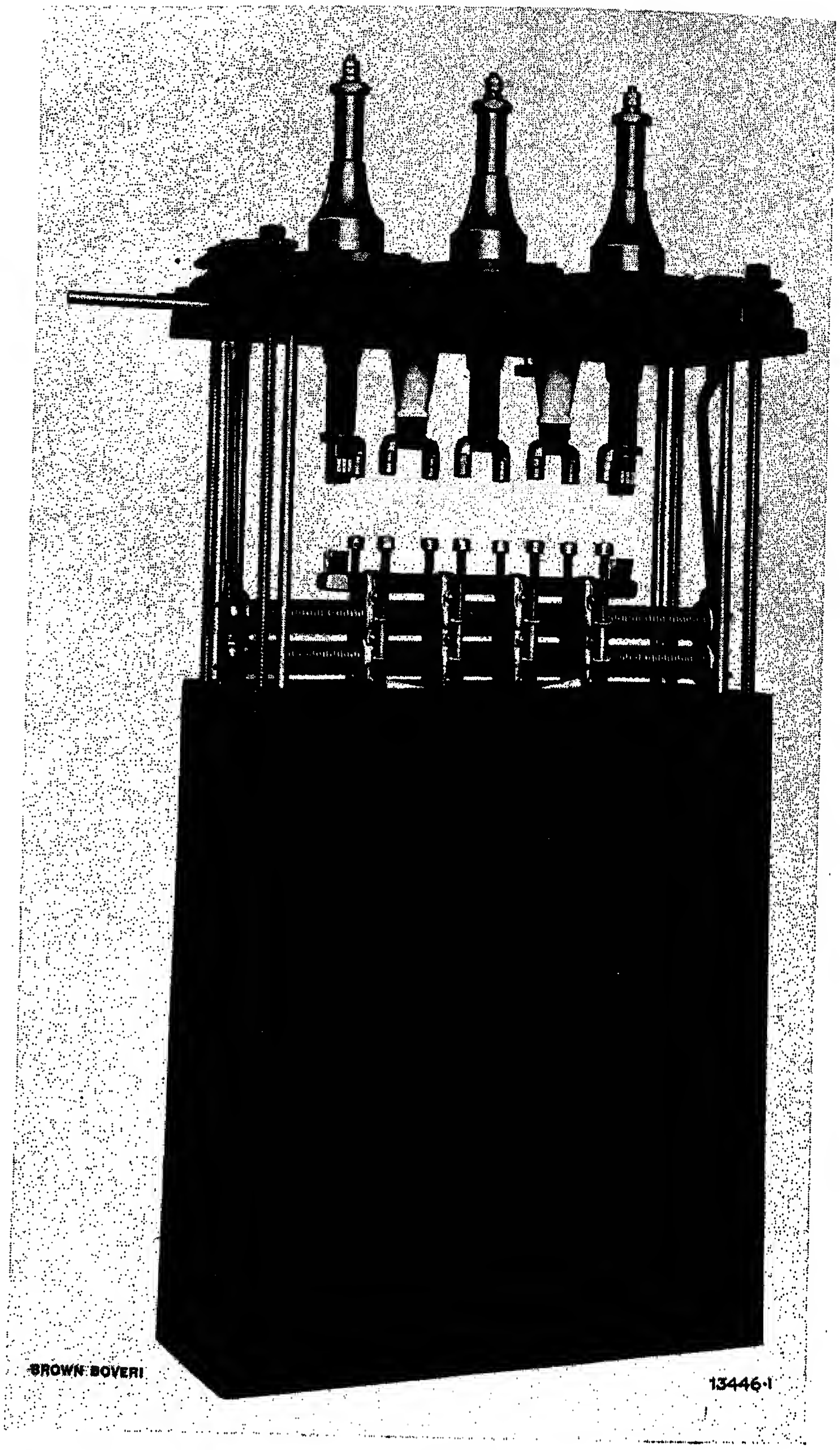


Fig. 2. — Single-pole oil circuit breaker, Type G 14, 50'000 V, 600 A, with third bushing, and containing a resistance for transformer protection.

to be entirely dead. The expansion apertures provided in the circuit breaker should be so arranged that the smoky gases liberated when a large current is interrupted do not pass across the insulators, as there would be a likelihood of a soot deposit being formed there under the influence of the tension, thus leading to a flashover.

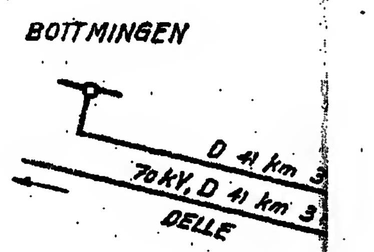
(c) Tripping on short circuit.

Oil circuit breakers used on large transmission systems should be able to open the circuit safely with the largest short-circuit load that can possibly arise at the place where they are installed. According to the setting of the relay and the purpose for

Parallel operation assumed
Kubel—NE. Switz. Supply Co.—
Supply Co.—Gœsgen—Lau

(Eglisau power station comprises two se

All impedances indicated are for 40 kV,
is taken of the excess-current pro



Determination of the sustained shor

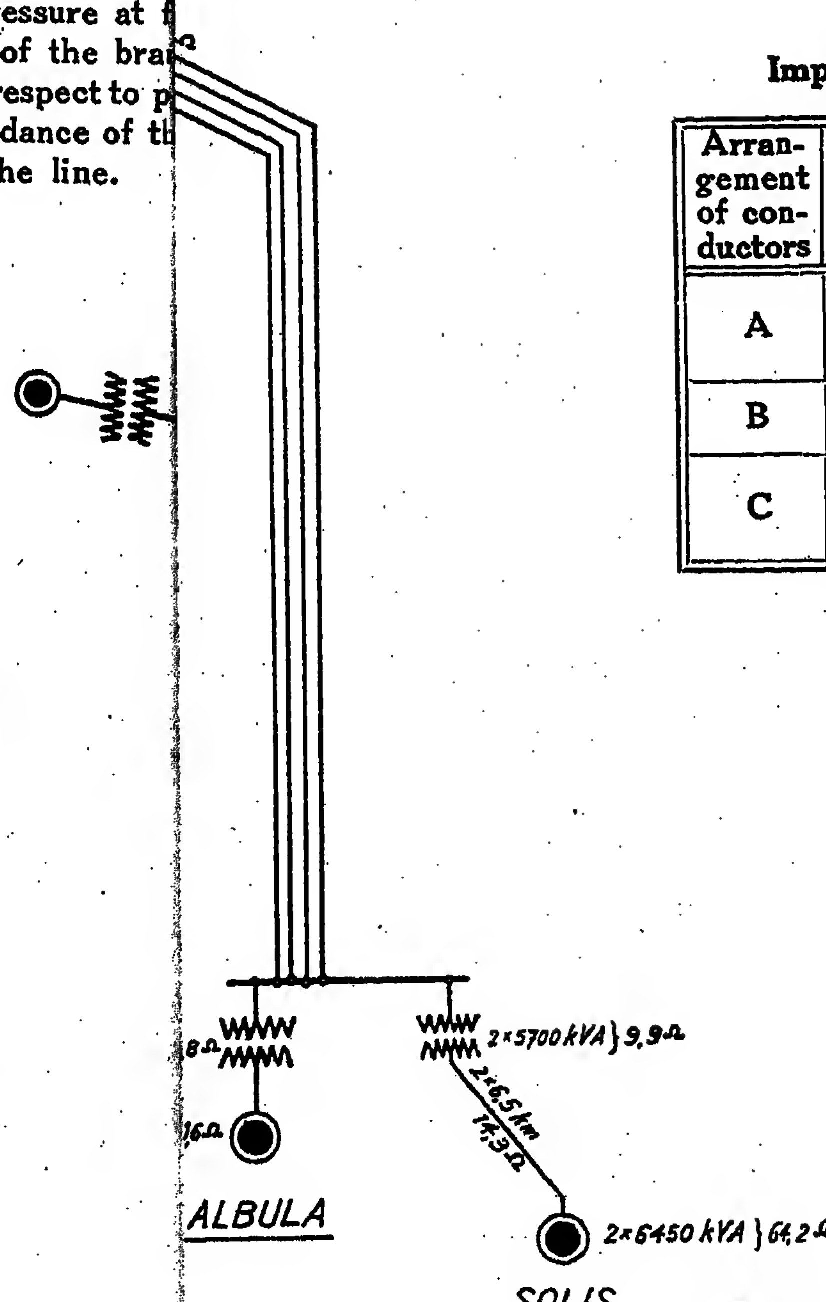
$$I_s = \frac{E_p}{Z} \text{ where}$$

I_s = sustained short-circuit curren

$E_p = \frac{E_L}{\sqrt{3}}$ = short-circuit phase pressure

Z = { For short circuits at a point o pressure E_L kV) with an $\boxed{Z_{50}}$ for the system, Z =
For short circuits on branch (power stations or substa
$Z = Z_{50} \frac{E_L^2}{2500} + Z_k$ }

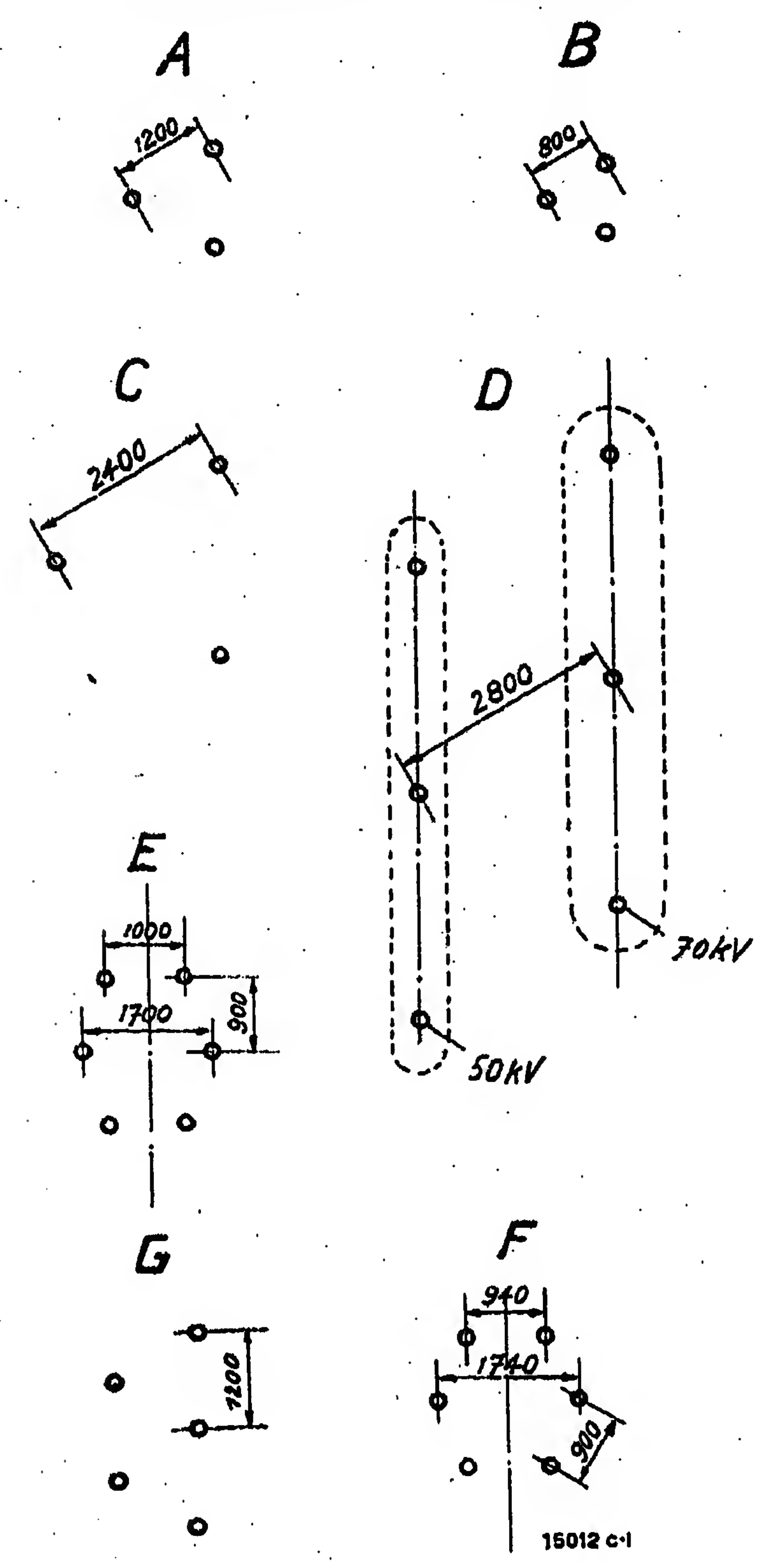
where E_L = working pressure at
Z_k = impedance of the bra point with respect to p of the impedance of t nected to the line.



Meaning of symbols:

$\boxed{\Omega}$ = short-circuit impedance (at the busbar in question).
ABCDEFG = Arrangement of conductors.
⊙ = Alternators.
WW/MM = Transformers.
kVA = Output.
Ω = Resultant impedance.

Arrangement of conductors:



Impedances for different cases.

Arrangement of conductors	Section of conductors	Z in Ω/km with respect to the line pressure
A	50 mm² Cu 63 mm² Cu	0·515 0·460 Ω/km
B	50 mm² Cu	0·494 Ω/km
C	50 mm² Cu 63 mm² Cu	0·548 0·494 Ω/km

experience gaine
form, which, or
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other, permits
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2. THE RE BRI

(a) Heating.

The heat of the circuit limit when th Breakers for vided with ac contact surfac while the sec must also be currents — up surfaces is have shown, sary. Even burned that excessive he is no neces to switches which the considering will only burned. T designed s away. Th formed wh great cons

(b) Insul

The site poles be rough plant. Sp between are sepa not be moulded is open, contacts Where is the c a depo a cond source

which it is provided, the value of the short-circuit load will be either the maximum initial current or the sustained short-circuit current.

It often happens in actual practice that it is not possible to tell whether or not the cause of the disturbance still persists after the breaker has tripped, and the quickest means of endeavouring to get the line working anew is to try putting the breaker in again. There is therefore the necessity of being able to close the circuit while a short circuit is still on the line, in which case the breaker immediately trips again. When the occasion arises, it must even be possible to close it several times in quick succession.

The question whether a switch is suitable for interrupting a given load can only be answered in the affirmative if it is still fit for service without any immediate touching-up after having tripped. Secondary effects observed, such as the production of smoke and the throwing out of oil, do not indicate that the apparatus is not ample enough, provided that they occur only to a moderate extent. It would be uneconomical to choose the breaker large enough to exclude all likelihood of oil being expelled through the expansion openings in the event of the most severe short circuit. The loss of oil must, however, not be so great as to impair the reliability of the circuit breaker after it has tripped a few times.

(d) Forces produced by heavy short-circuit currents.

When the current exceeds about 10'000 A, the electro-dynamic forces set up are considerable, and must be taken into account when designing the circuit breaker. These forces act partly on the contact bar and partly on the contacts themselves; the action on the latter may be very great if the apparatus is incorrectly designed. It is not only when the breaker trips that these forces come into play, but also when it is in and when it is closed on a short circuit. The mechanical forces developed by the maximum instantaneous value of the short-circuit current must consequently be reckoned with, and these can amount to several hundred kilograms. The contact bar and the operating mechanism connected to it have therefore to be strong enough to resist the sudden stresses corresponding to such a force. Moreover, the latter opposes the movement of the contact bar when the breaker is closed on a short circuit, and the operating gear must therefore be designed to allow of bringing the breaker into the closed position against the action of the forces exerted by the short-circuit current.

The forces at the contacts act on the main contacts when the breaker is closed, and on the arcing contacts at the moment of switching in while a short circuit is on the line. Their maximum value is that corresponding to the instantaneous short-circuit current. The forces always act in such a way that they tend to make the contacts come apart.

If separation of the main contacts takes place, there is a liability of their being burned. With switches of large current-carrying capacity, however, the brushes are very massive, and it is a comparatively easy matter to design the apparatus so that parting of the contacts is prevented.

The dangers due to the forcing apart of the sparking tips when the breaker is closed on a short circuit are: the formation of an arc with the largest short-circuit current, and consequently over-stressing of the switch; burning of the main contacts, even when these work quite satisfactorily; fusing together of the sparking tips, as these are pressed against one another with surfaces which are partly in a molten state.

To prevent the sparking tips from being separated, it is necessary to take special precautions with circuit breakers for large currents. For instance, it is possible to reduce to a certain value the forces tending to part the contacts by suitably arranging the movable portions of the latter and the leads belonging to them. The pressure of the contact spring must be at least equal to the value in question. In Brown Boveri oil circuit breakers, this point has been given special attention, and investigated carefully by means of tests and also mathematically. The contacts of these switches are furnished with springs having a large initial compression, so that sufficient pressure is available to obviate all chance of the contacts being forced apart by a heavy short-circuit current at the moment the breaker closes the circuit.

3. EFFECTS DUE TO THE FORMATION OF THE ARC IN OIL.

(a) Arcing energy.

For an arc to persist, it is necessary to have a certain potential, i. e., the arc pressure e. At any moment, the arc therefore absorbs an amount of power equal to $e \times i$, where i is the instantaneous value of the current flowing. The energy A expended during the time t_L the arc lasts is

$$A = \int_0^{t_L} e\, i\, dt$$

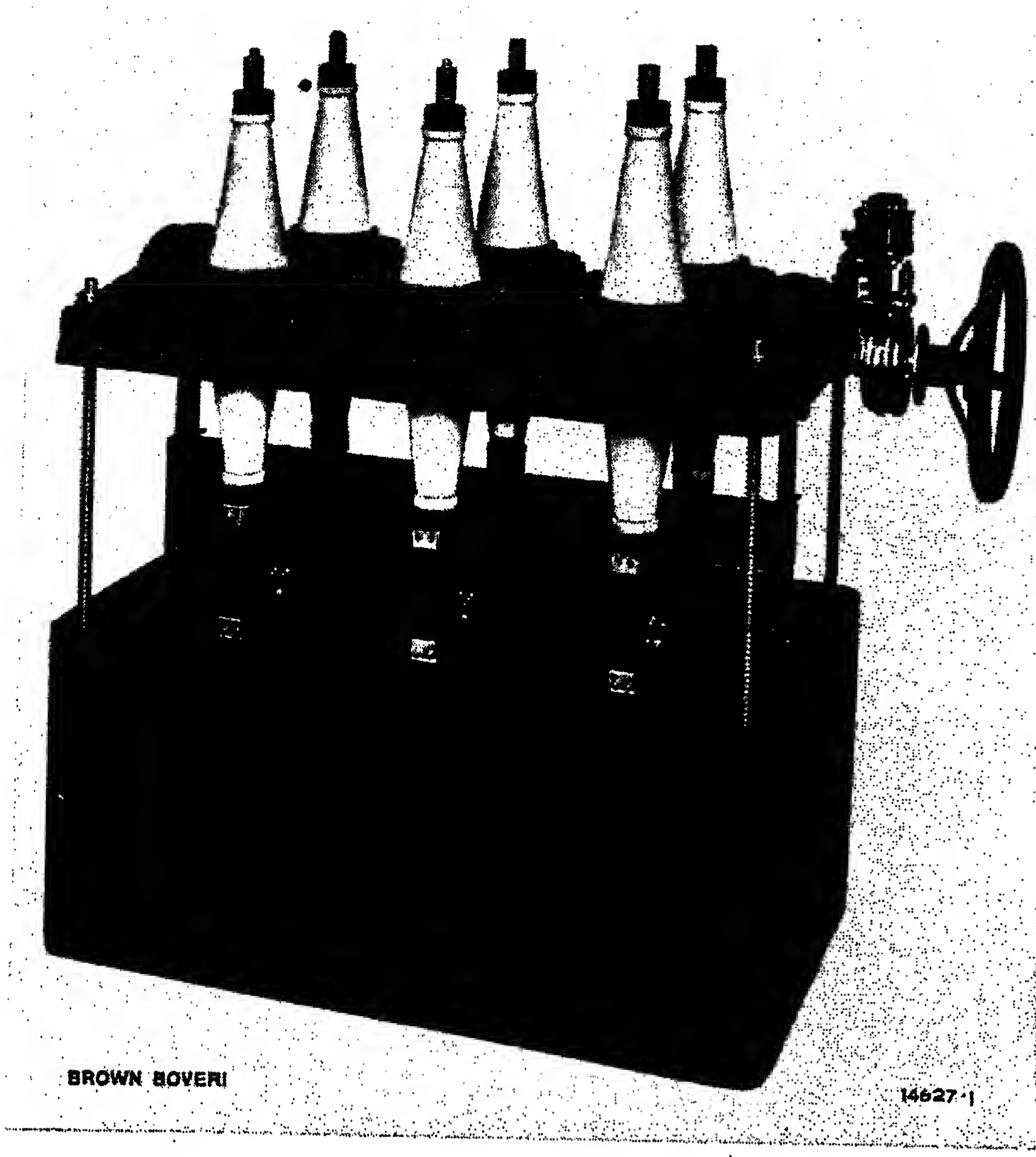


Fig. 4. — Triple-pole oil-switch, Type A 12/3 a, 35'000 V, 350 A, with insulating partitions between phases and insulating lining for tank.

This is called the *arcing energy,* and represents the electrical energy which is converted into heat, mechanical, and chemical energy during the rupturing process. These three forms of energy are the cause of the undesirable occurrences accompanying the arc. The value of the arcing energy has, therefore, a certain importance, as it is a measure of the deleterious effects of the arc. One of the greatest problems in the design of oil circuit breakers is to keep it as low as possible.

The extent to which the arc spreads, and consequently the space it requires in the apparatus, is also dependent on the arcing energy. Abnormal spreading of the arc can lead to a flashover to the tank or from one phase to another. Brown Boveri oil circuit breakers for heavy duty are provided with insulating plates between the contacts and with an insulating lining for the tank. The possibility of trouble arising during the rupturing process, due, for instance, to the arc being deflected to the side by the electro-dynamic forces set up, is therefore reduced to a minimum. Fig. 4 shows an oil circuit breaker, Type A 12/3 a, of standard design with insulating partitions.

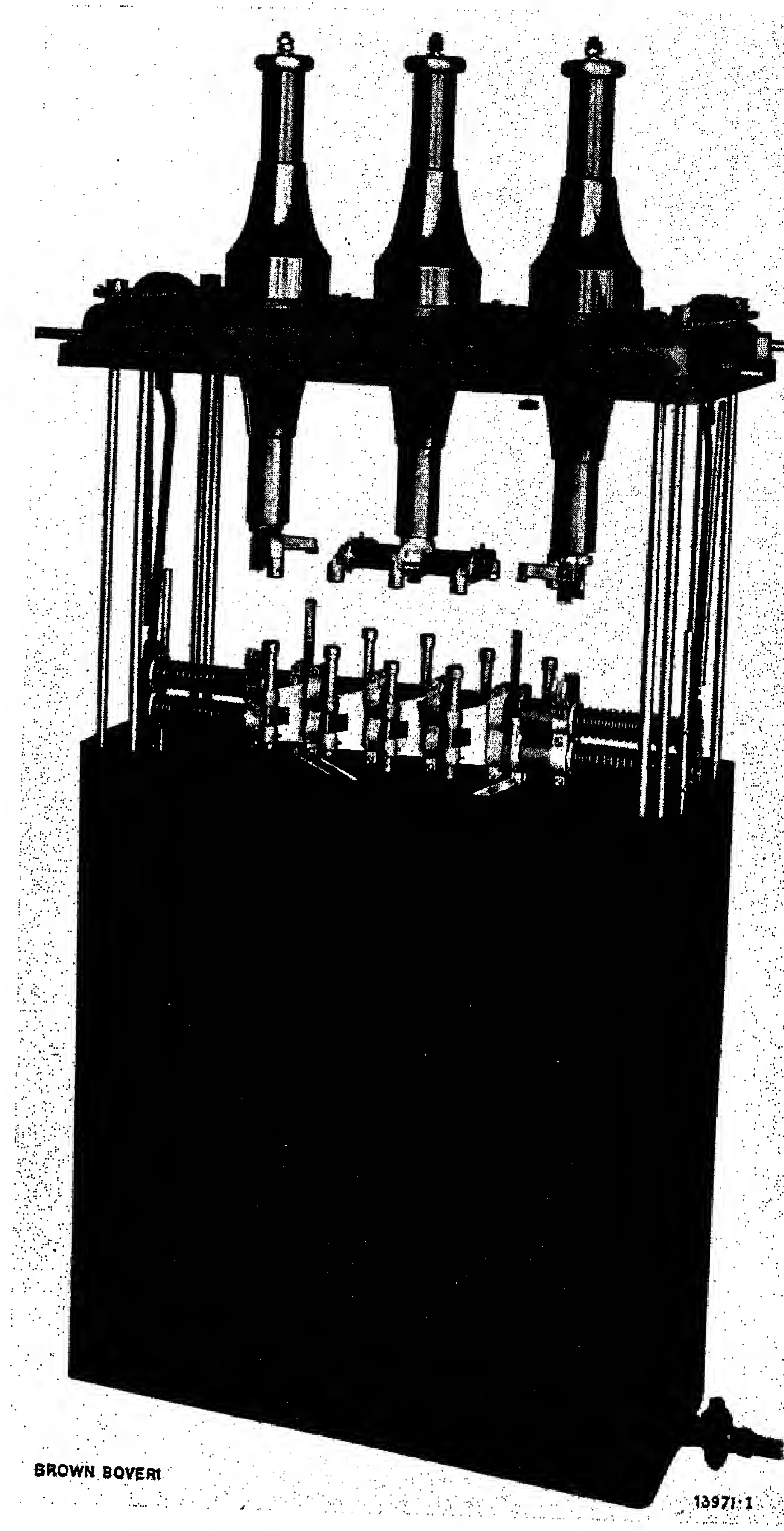


Fig. 5. — Single-pole oil circuit breaker, Type G 18/1 b, 80'000 V, 350 A, with third bushing.

(b) Production of gas and soot.

The oil in the neighbourhood of the arc is not only vaporised by the high temperature but is actually decomposed. A chemical separation of the hydrocarbon oils takes place: hydrogen and light hydrocarbon compounds in gaseous form[1] and solid carbon in the form of soot are liberated. The latter partly escapes with the gases as a dark smoke and the remainder causes dirtying of the oil. This lowers

[1] For further particulars see: Dr. Bruno Bauer, "Die thermodynamischen und chemischen Vorgänge beim Abschaltprozess", Bulletin of the S. E. V., 1917, pp. 230 ff.

the insulating strength of the latter, but not in such a way that is has any effect on the operation of the breaker under normal conditions; in fact the carbon particles sink gradually in the undisturbed oil, and are deposited on the bottom of the tank in the form of fine sludge.

The gases generated are inflammable and more or less explosive according to the amount of air with which they become mixed. They are the cause of switch explosions. In order to avoid these it is necessary to prevent the gases being ignited above the surface of the oil. This means that there must be a sufficient height of oil above the contacts to exclude all possibility of the arc or flame reaching the surface, and also to cool the rising gas bubbles down to a temperature lower than that necessary for ignition before they come into contact with the air.

(c) Pressure impulses in the oil.

The gasifying of the oil at the arc causes a sudden increase of volume. This acts like an explosion

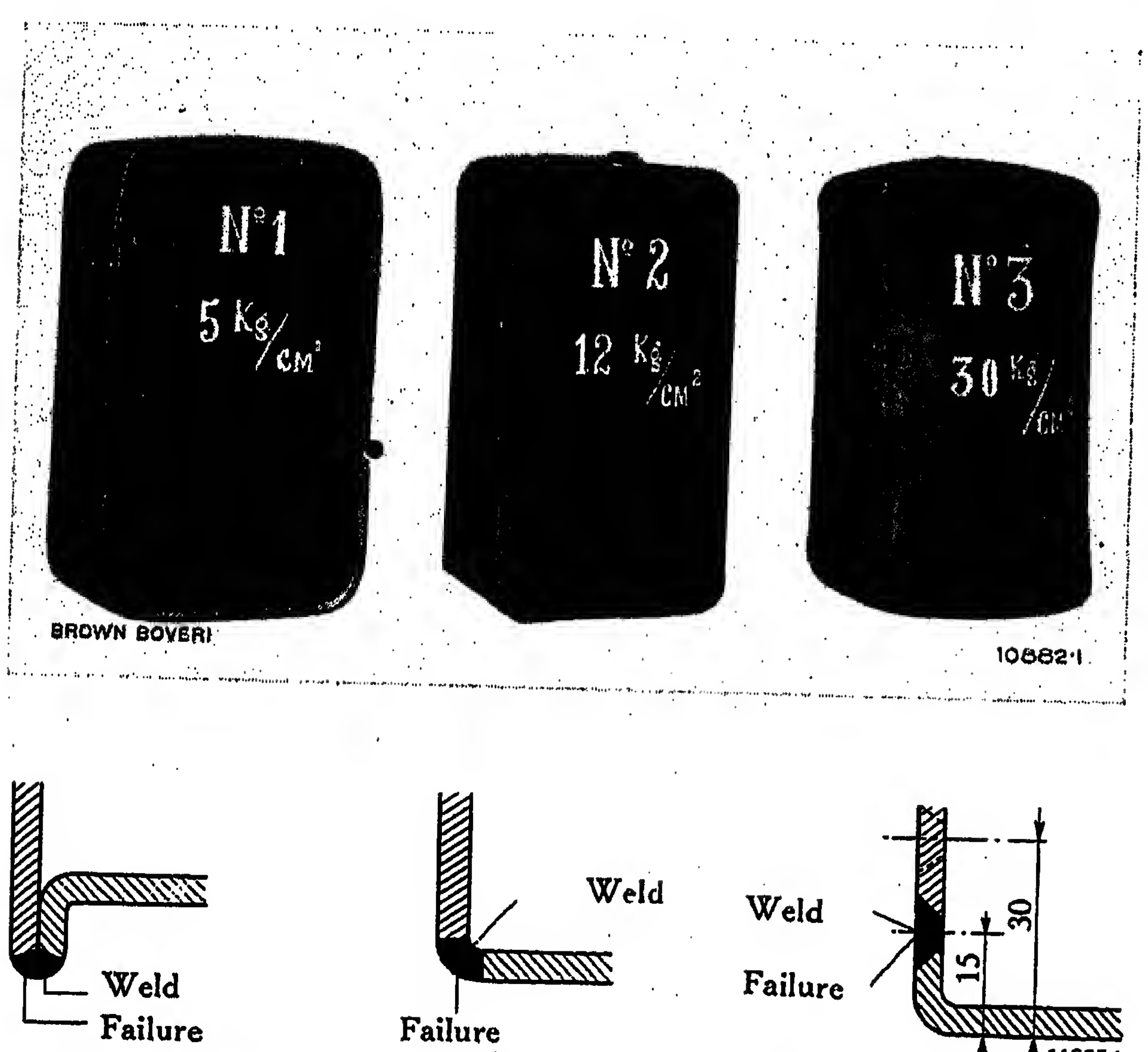


Fig. 6. — Sheet iron tanks with different kinds of welded joints, after subjection to internal pressure tests.

and consequently produces pressure impulses which spread from the arc in waves through the oil to be taken up by the tank. These impulses oscillate at a high frequency, and their strength is quite considerable. During tests with a Brown Boveri oil circuit breaker, pressures up to about 8 kg per cm^2, oscillating at the rate of 500 periods per second, were measured. Their amplitude at this high frequency is, however, small.

Only the tank is stressed by these pressure impulses, and it must either be strong enough to resist the greatest pressures arising, or be sufficiently elastic to bear the momentary strains without permanent change of shape.

The parts most endangered are the welded joints. Brown Boveri oil tanks are butt welded, and the joint in the bottom is not at the bend, but a little above it (patent applied for in all the principal countries). Fig. 6 shows some tanks used for testing purposes and the arrangement of the welds. The pressure necessary to make the joint give way is indicated on each tank in the illustration.

(d) Burning of the contacts.

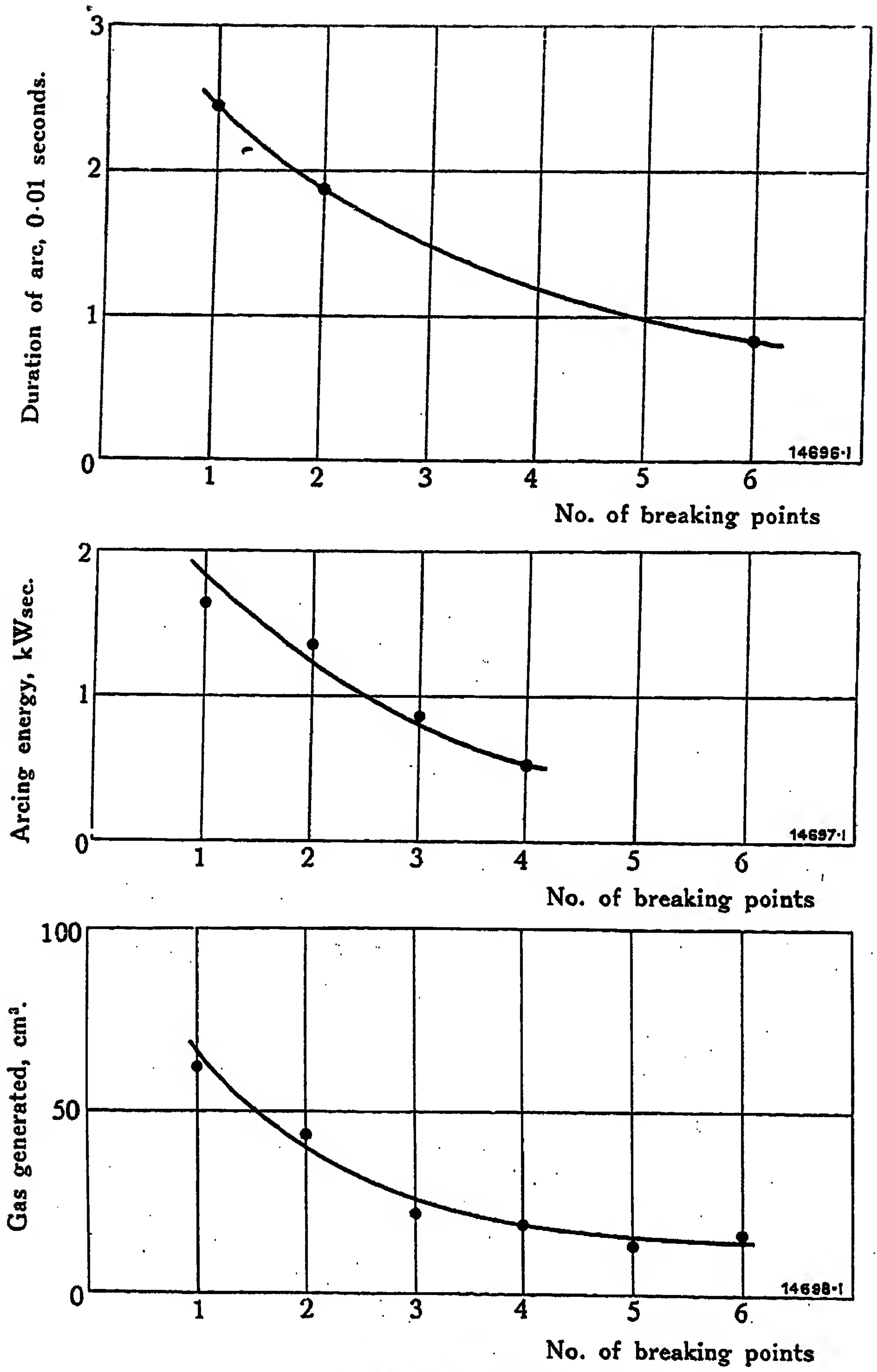
The amount of burning is not so much dependent on the load as on the current. The arcing contacts of Brown Boveri oil circuit breakers are of such massive design that there is no need to change them before the complete breaker requires its regular overhaul.

4. INFLUENCE OF CONSTRUCTIONAL AND OTHER DETAILS ON THE BREAKING PROCESS.

(a) Number of breaking points.

The breaking process can be facilitated by increasing the number of breaks in series with one another. The improvement is for the most part due to the reduction in the length of the arc, which means a lower arcing energy and a smaller amount of gas generated. Comparative tests made by Brown, Boveri & Co. with small and purely inductive loads of about 500 A at 1400 V, that is 700 kVA, single phase, gave the results plotted in Figs. 7a—7c. The speed of breaking amounted to about 0·7 metres per second. The intensity of the pressure impulses in the oil with several arcing gaps was only slightly lower than when they are less numerous. The results of these tests show that the conditions during the rupturing process can be considerably improved by increasing the number of arcing gaps.

The extent to which these results can be taken as giving an indication of the conditions when breaking larger outputs is not yet fully settled. Some information on this question is contained in section 7 of the present article. It can be taken as fairly certain that an increase in the number of arcing gaps will, in all cases, be accompanied by a fall in the arcing energy and in the volume of gas generated. Multiple gaps have also the advantage of dividing up the places at which gas is formed, with the result that the latter is better cooled by the oil. The tests



Figs. 7 — a, b, c.
Duration of arc, arcing energy and gas generated when breaking 500 A, 1400 V, that is, a single-phase inductive load of 700 kVA.

have shown that the height of oil above the contacts necessary to prevent the flame rising to the surface can be smaller with several arcing gaps; or by leaving the depth the same as is essential with only single or double breaking, the reliability of the apparatus can be increased.

It is especially advantageous to have multiple breaks with high-tension switches, as here, the length and duration of the arc are correspondingly greater.

(b) Consistency of the oil.

Variations of the viscosity, such as occur in switch oils at ordinary temperatures, do not influence the breaking process to any extent. The question of change in viscosity when the temperature falls very low is, however, of great importance. Oil that sets in such cases is a source of danger when a breaker trips near the limit of its capacity, as it impairs the breaking process for two reasons; the speed of separation of the contacts is retarded, and the oil cannot flow in quickly enough to extinguish the arc. It is therefore essential to prevent the temperature of the breaker from falling too far, or to use only oils whose setting point is not higher than the lowest temperature likely to occur under working conditions. Tests

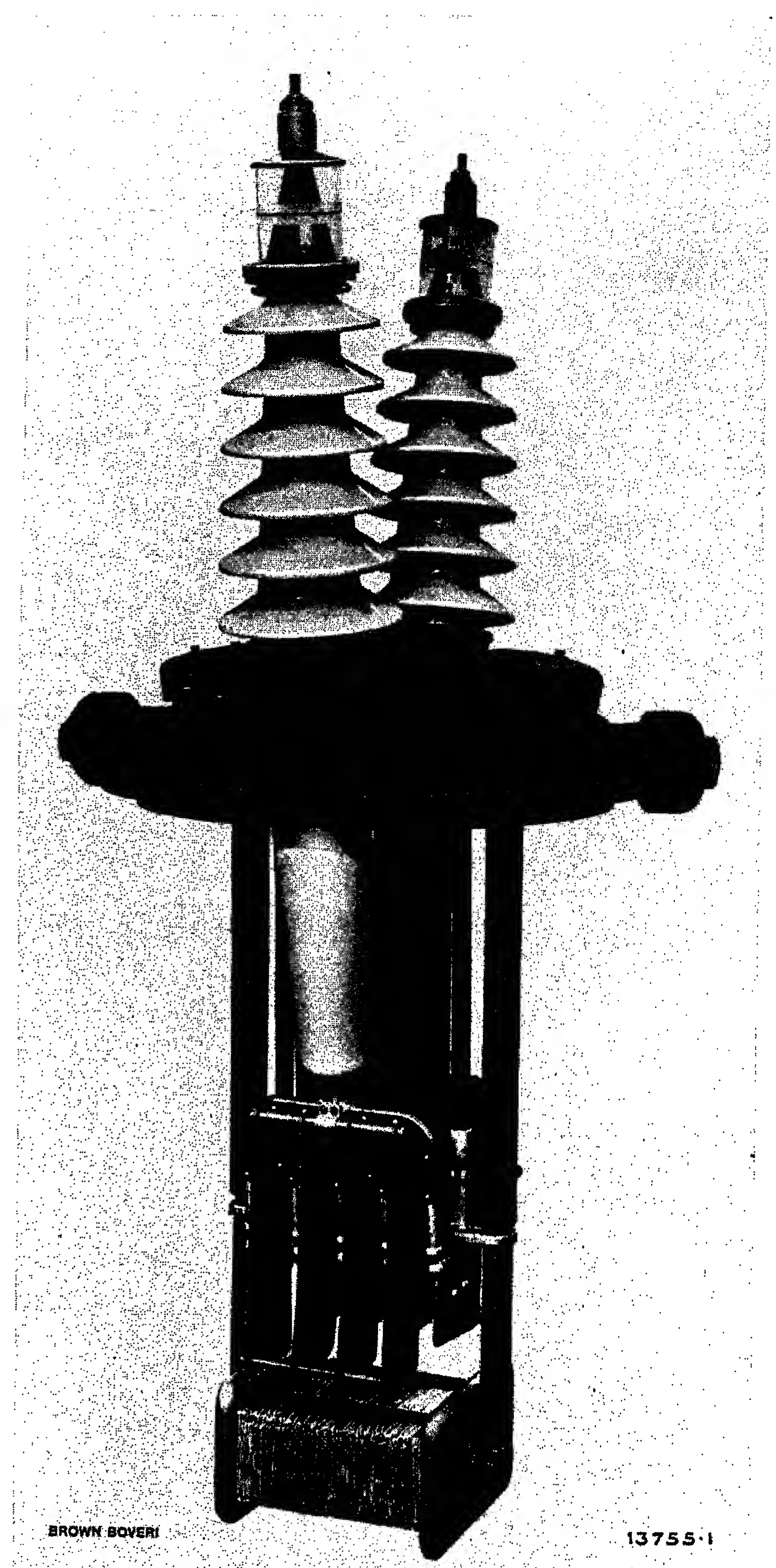


Fig. 8. — Single-pole oil circuit breaker of outdoor type, 110'000 V, 350 A, with tank removed. Below is a resistance for transformer protection, and somewhat above this can be seen the contacts in the "closed" position.

on the effect of thickening of the oil in switches, as well as data on the setting point, are to be found in The Brown Boveri Review, January, 1922.

(c) Other characteristics of the oil.

The flash point and the burning point are of no special importance as regards the breaking process and the danger of explosion. All the same, it is as well not to have them too low, on account of the chance of vapour being produced through possible overheating of the switch.

The dielectric strength of the oil depends largely on the condition of the latter (sludge, dust, or moisture in suspension). Within the limits met with in practice, however, the variation of dielectric strength is of no great importance for the rupturing process, since all insulation in the neighbourhood of the arc must, in any case, be liberally dimensioned with respect to the working pressure. Nevertheless, there should not be an excessive amount of sludge or dust, especially if moisture is present, on account of the possibility of flashovers occurring along the insulating parts, such as the contact bar, for instance. Soot and especially damp dust particles collect on the surfaces of the insulating parts, due to the effect of the electric field, and can eventually form conducting paths.

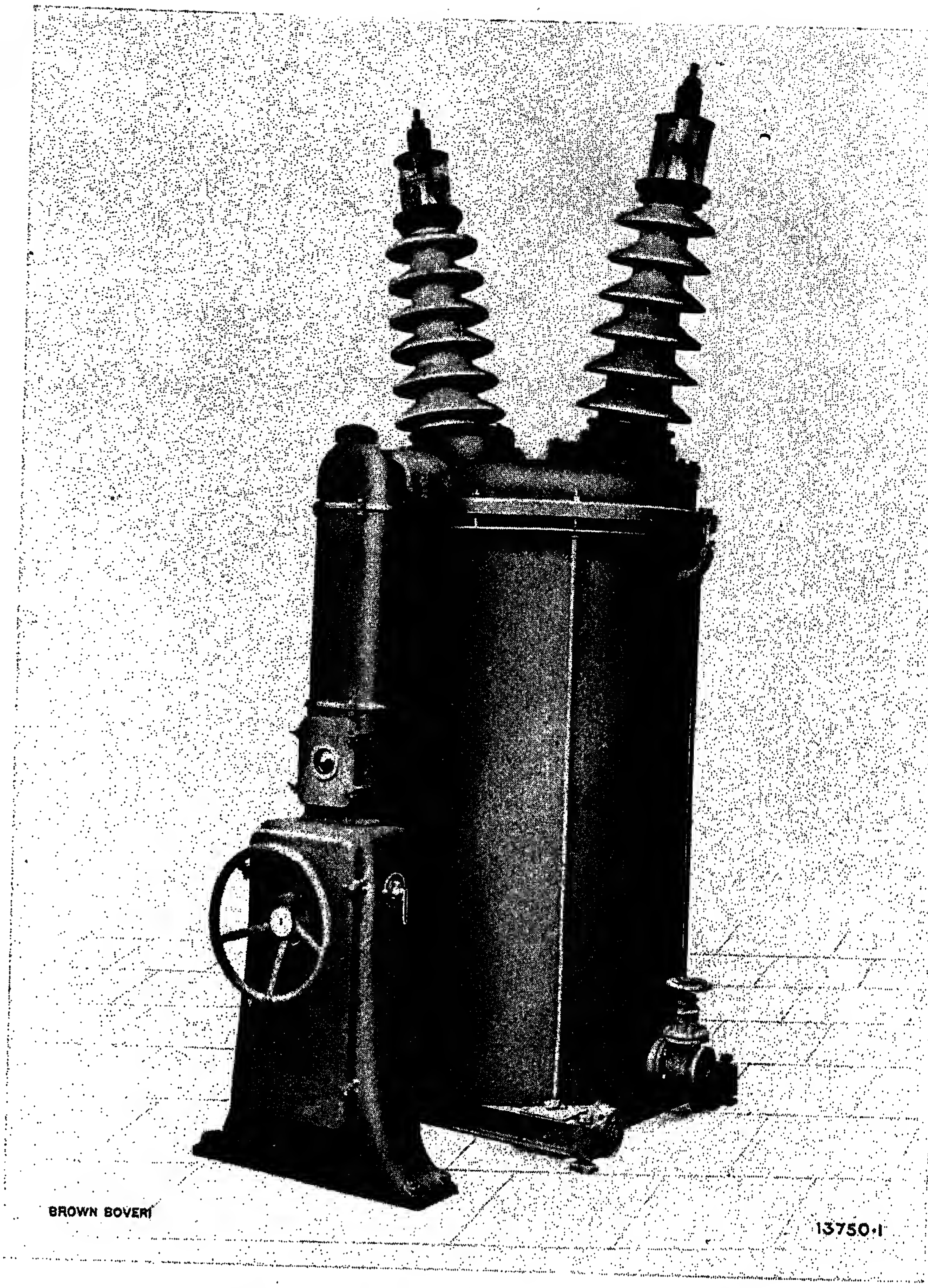


Fig. 9. — Single-pole oil circuit breaker of outdoor type, 110'000 V, 350 A, with control pillar and transporting truck.

(d) Static pressure in the oil.

From tests made by Brown, Boveri & Co. with an explosion-proof switch breaking an inductive load of 700 kVA, it was found that with a gauge pressure of 7 kg per cm^2, the length and duration of the arc were 1·7 times, the arcing energy at least 5 times, and the volume of gas generated more than 20 times the corresponding values at atmospheric pressure. Dr. Bauer also found that the conditions during breaking were much less favourable when the pressure in the switch tank was raised to about the extend mentioned.

The claim frequently advanced that quenching of the arc could be rendered more easy by raising the pressure in the switch tank is contradicted by the above results, at least in so far as moderate pressures are concerned. The question of the effect of very high pressures must, however, remain open for the present.

5. THE USE OF RESISTANCES FOR PROTECTING THE CIRCUIT BREAKER.

(a) Purpose of the resistances.

The rupturing capacity of an oil circuit breaker can be raised to at least four times the normal amount if it is fitted with resistances of low ohmic value.

(b) Design of the resistances.

Such resistances take up a fair amount of space, as they have to be large in order to obtain the necessary heat capacity. Consequently, they must be mounted outside the breaker. Resistances of the kind in question

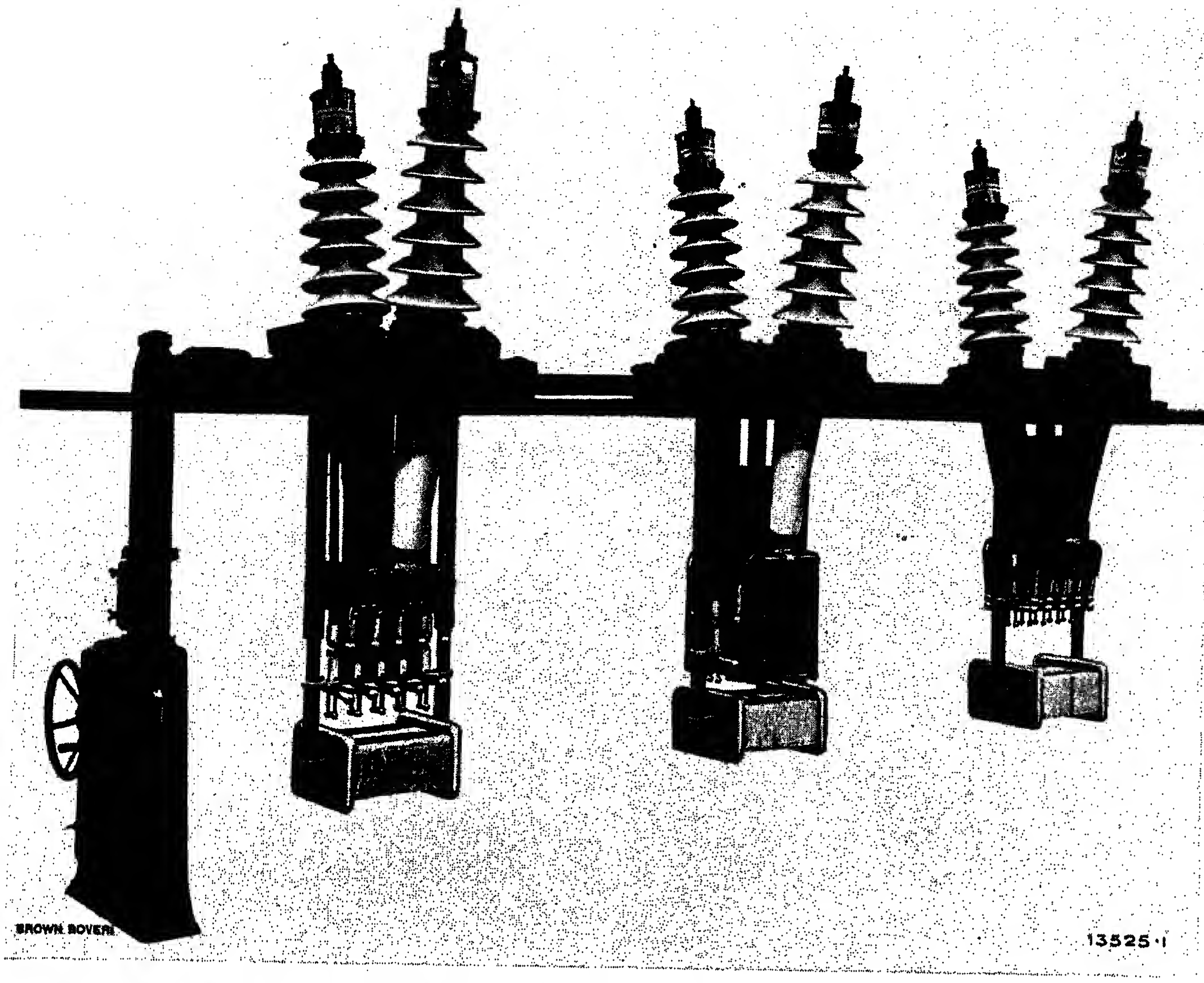


Fig. 10. — Three single-pole oil circuit breakers similar to that in Fig. 9, with common control pillar. (Tanks removed.)

have elements of wire or of metal ribbon with heat-proof asbestos insulation.

For connecting up the resistances it is necessary to provide the breaker with a third bushing for each pole. The arrangement of the connections is shown in Fig. 11.

Hitherto, the contacts of the two breaking stages were set at different levels, so that stages I opened first. Brown, Boveri & Co. now make their oil circuit breakers with all the contacts at the same level, thereby reducing the time the resistance is loaded and thus permitting a smaller resistance to be employed, while the quenching of the arc is found to remain just as favourable.

Resistances for breaker protection can be used conjointly with resistances for protecting the transformers (see section 6). In such cases, the breaker has an auxiliary contact arranged to that its closing distance is about 20 mm less than that of the rupturing contacts, as indicated in Fig. 13.

(c) Effect of resistances for breaker protection.

An alternating-current arc is always extinguished at the moment when the current curve passes through zero. The momentary quenching that takes place at first is immediately followed by the arc being struck anew as soon as the current rises again, this effect depending on the rapidity with which the tension increases after the instant at which the current is zero. The advantage of the resistance is that it retards the speed of the pressure rise. Fig. 12 gives the current and pressure curves at both breaking stages with the breaker opening on a short circuit. The electrode tension at stages I is equal to that across the terminals of the resistance, i. e., it is proportional to the current flowing in the latter. It is not possible for the electrode tension to rise suddenly to its maximum value at the instant the arc is extinguished, — as would happen if no parallel resistance were employed, — since the growth of the current in the resistance is hindered, as it depends on the relation between the ohmic value of the resistance and the reactance of the system in which the short circuit has taken place. The other stages, II, deal with the current in the resistance, which is smaller. It is nearly in phase with the pressure when the resistance is large compared with the reactance. Since the pressure curve then passes through zero at the same time as the current curve, the growth of the pressure at stages II is also slow. The greater the resistance is, the slower will the pressure increase, whereas at stages I the opposite is the case.

(d) Dimensioning the resistances for breaker protection.

The favourable influence of the resistance on the rupturing process is a maximum when there is a

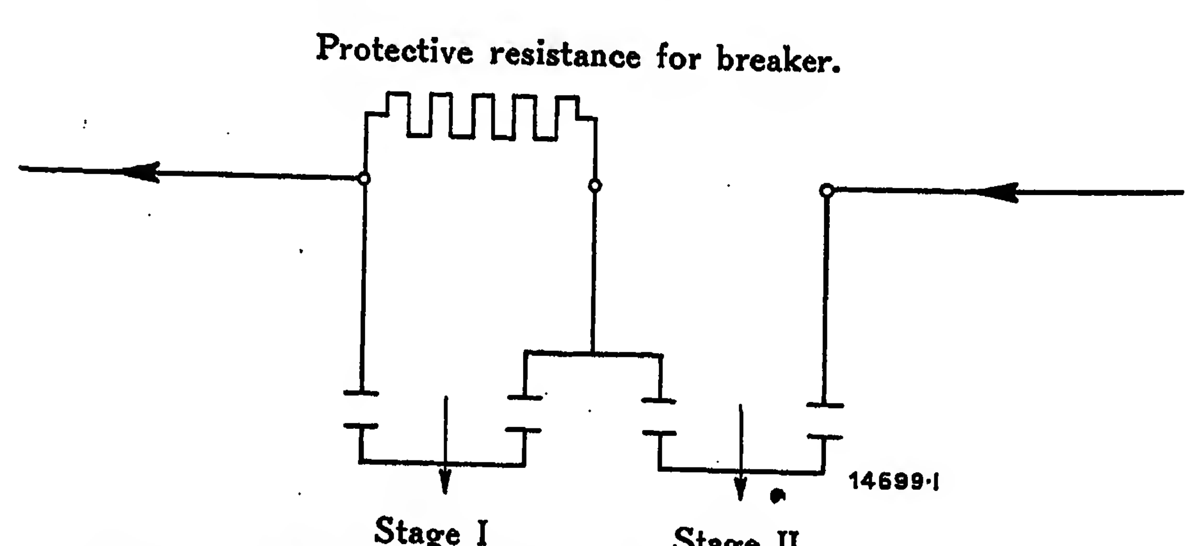


Fig. 11. — Diagram of a breaker with protective resistance.

certain appropriate relation between the ohmic value of the resistance and the reactance of the line where the short circuit is. For the sake of simplicity, it is usual to reckon with the impedance, i. e., the impedance with a sudden short circuit, instead of the reactance. Brown, Boveri & Co. have found from the tests described in section 8 b that the most favourable value for the resistance is 8 to 10 times the short-circuit impedance.

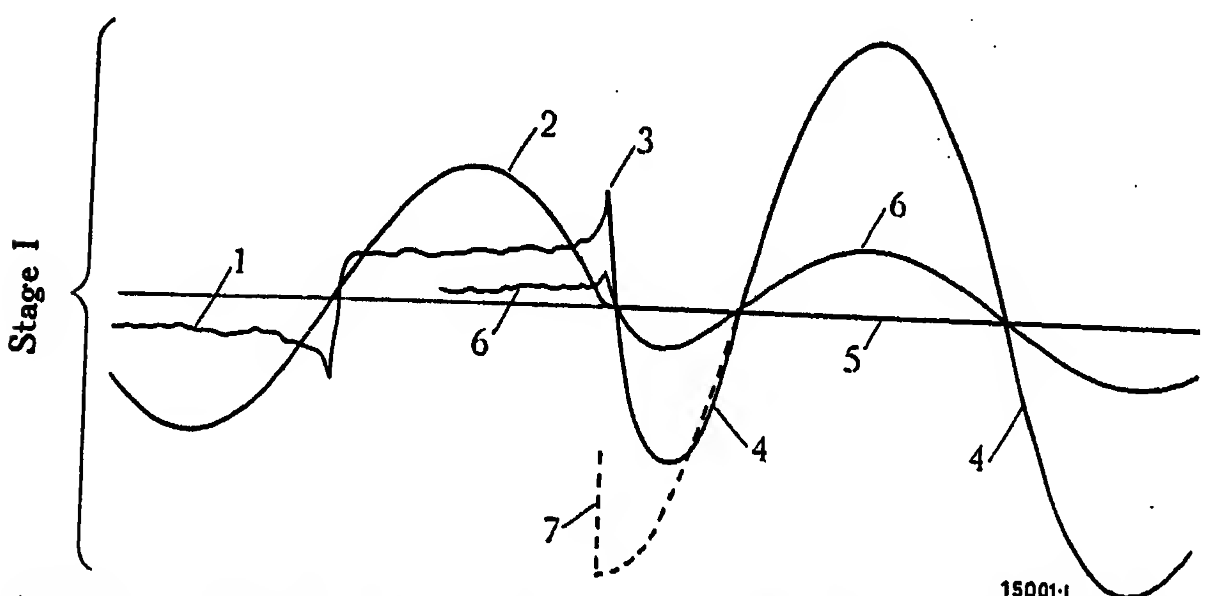


Fig. 12 a. — Pressure and current when a breaker having a protective resistance is tripped by a short circuit.

1. Pressure of the arc.
2. Current in the arc.
3. Extinction of the arc.
4. Pressure at electrodes and resistance.
5. Zero line for current in the arc.
6. Current in the resistance.
7. Pressure curve without a resistance.

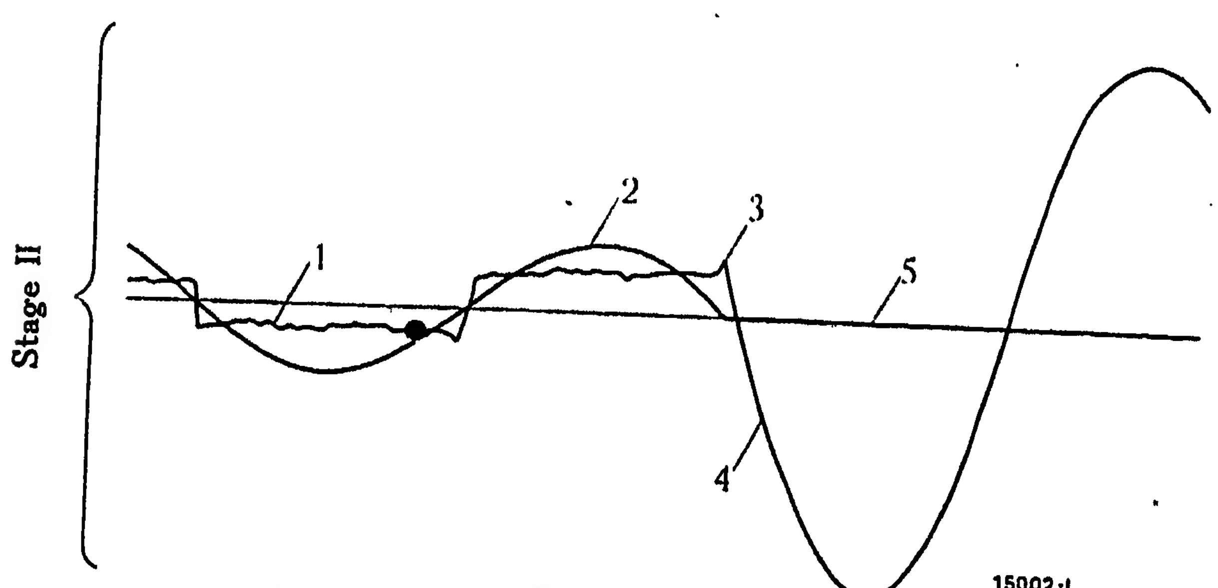


Fig. 12 b. — Pressure and current when a breaker having a protective resistance is tripped by a short circuit.

1. Pressure of the arc.
2. Current in the arc.
3. Extinction of the arc.
4. Pressure at electrodes.
5. Zero line for current in the arc.

The resistances are so dimensioned that they do not overheat when the breaker is reclosed and opens again automatically three times in quick succession on a short circuit of any magnitude that can occur.

(e) Employment of resistances for breaker protection.

The resistances described are used practically only for single-pole breakers. Their adoption will generally be considered in cases where the load that might have to be broken is higher than could normally be dealt with by an ordinary breaker for the working tension in question if no resistance were provided. But even here it may be found more advantageous to instal a switch of larger breaking capacity rather than to add a resistance. The decision will be governed by local conditions and the comparative cost of each alternative.

6. FITTING THE BREAKER WITH RESISTANCES FOR TRANSFORMER PROTECTION.

(a) Purpose of the resistances.

Over-potentials can arise when unloaded transformers or transmission lines are switched in and out. While switching in, there can also be rushes of current. It is possible to obviate such occurrences — which can be a source of danger for the plant under certain circumstances—or to reduce them to an unimportant amount by providing resistances having a high ohmic value. When it is remembered that mechanical contrivances in which undamped shocks regularly occur are avoided to the utmost extent, it is not difficult to see that everything reasonably possible should be done in electrical plants to prevent surges and the like from taking place when the apparatus is operated in the regular manner. In American practice, this point does not seem to receive the consideration it merits, and the use of protective resistances is practically unknown there. The large over-potentials occurring when transformers are switched in make the employment of protective resistances necessary in many instances, whereas, when unloaded transmission lines are switched in with breakers like those of the Brown Boveri type, having a sufficiently large number of breaking points and a high closing speed, protective resistances can be dispensed with. These facts have been confirmed by various tests which have been carried out.

(b) Design of the resistances.

The resistances in question are generally placed inside the tank of the breaker. The connections are

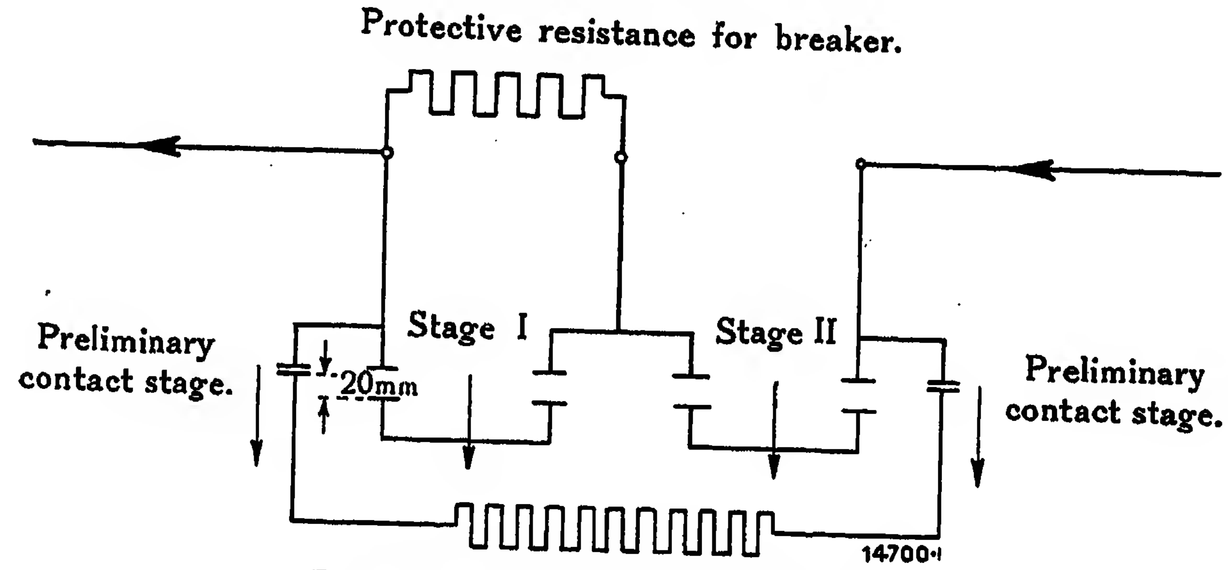


Fig. 13. — Diagram of a breaker with protective resistances for breaker and transformer.

shown in Fig. 13, which refers to a breaker having at the same time resistances for its own protection.

Transformer protecting resistances are composed of a series of wire elements insulated with presspan.

(c) Dimensioning the resistances for transformer protection.

The most favourable value of resistances for use when switching in is not equally appropriate when switching out. It has been proved by tests, however, that a resistance of mean value gives a sufficiently favourable effect in both cases. This value R in ohms was found to be:

$$R = 0{\cdot}90 \frac{E_p}{I_m}$$

where E_p is the phase pressure and I_m the magnetising current.

(d) Employment of resistances for transformer protection.

The use of these resistances is recommended with transformers which are normally switched in and out when the secondary circuit is open. For reasons of cost, they are not always thought essential in the case of low powers and pressures, but this consideration should not be allowed to carry any weight with extra-high-tension apparatus.

7. CONSEQUENCES OF CHOOSING TOO SMALL A CIRCUIT BREAKER.

The duty to which the breaker is exposed depends on the load and the power factor at the time when tripping takes place. The power factor is very low with a short circuit, and variations from 0 to about 0·4 do not make any great difference. The rupturing capacity P_p per pole in kVA at breaking is

$$P_p = I\,E_p$$

I being the current in amperes when the arc starts, and E_p the pressure in kV between the terminals of one pole of the breaker immediately after the circuit is completely broken. It should be mentioned here that, with three-phase systems, the pressure at the pole where the arc is first quenched rises (to about $1^1/_2$ times the normal pressure) until the circuit is completely broken in the other phases.

If the breaking capacity is not ample enough for the conditions under which the apparatus has to operate, it can be damaged or destroyed by gas explosions, flashing-over of the arc to the sides of the tank or other parts, or by pressure impulses in the oil. Fires due to burning oil have also to be reckoned with, and these can have most undesirable consequences for the whole switch-room by reason of the quantity of smoke produced, melting of conductors, destruction of insulators, etc.

It is possible to build explosion-proof circuit breakers that can withstand explosions and burning of the

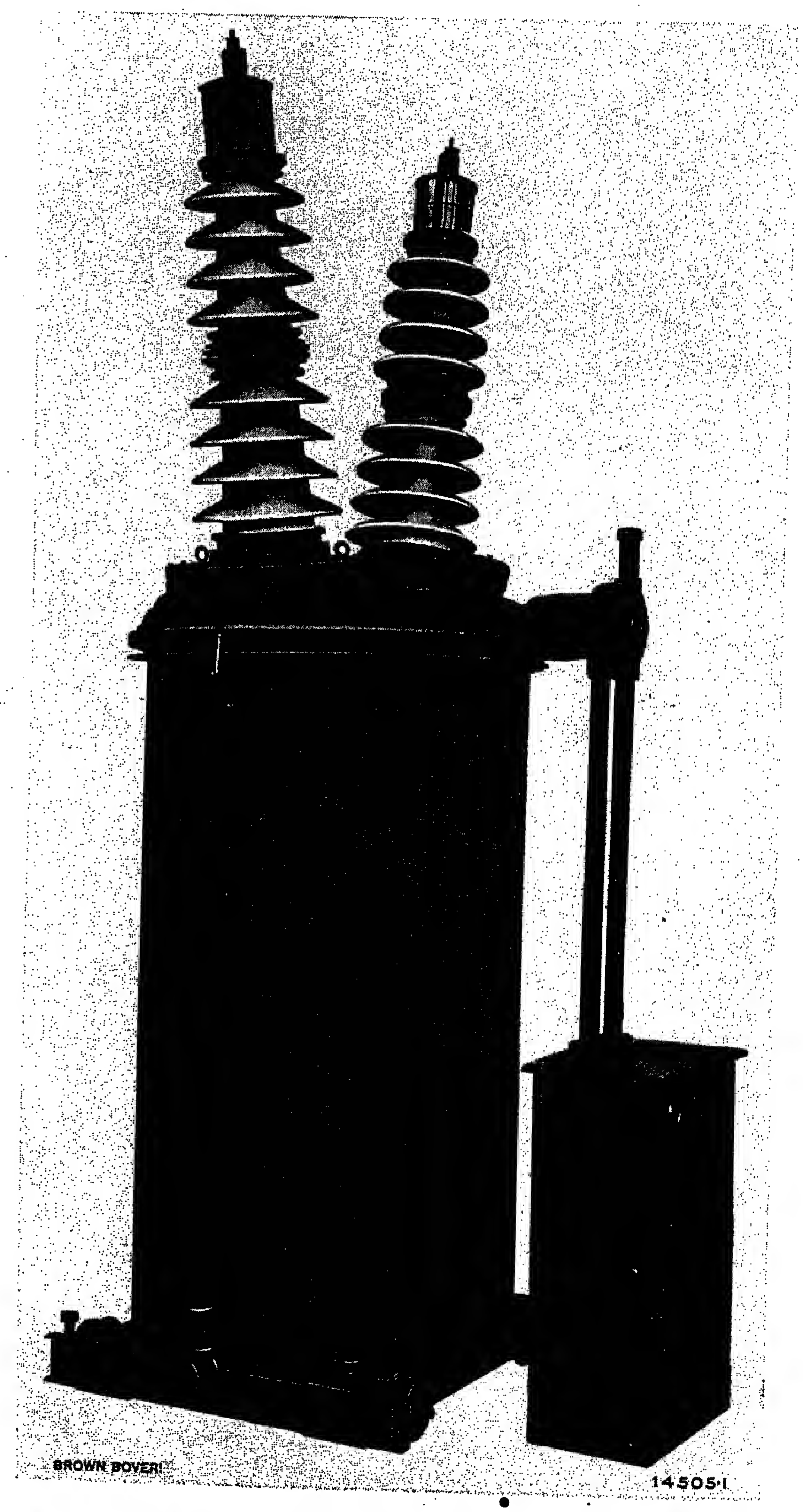


Fig. 14. — Single-pole oil circuit breaker of outdoor type 150'000 V, 200 A, with control pillar and transporting truck.

oil. "Explosion-proof" is here taken to mean a design which is calculated not only for the pressures arising when the breaker trips on a short circuit, but one which can also withstand the maximum pressure due to an explosion. The highest pressure likely to be met with when a gas mixture is ignited in the apparatus is about 12 kg per cm^2. It is obvious that the price of a breaker is considerably increased when it is made explosion proof; further, for this type a round tank is more suitable than the rectangular form. Such breakers therefore take up more space when mounted in a row, and the cost of the switch-room is thereby increased. For this reason it is preferable to adopt liberally-dimensioned breakers of the more usual design.

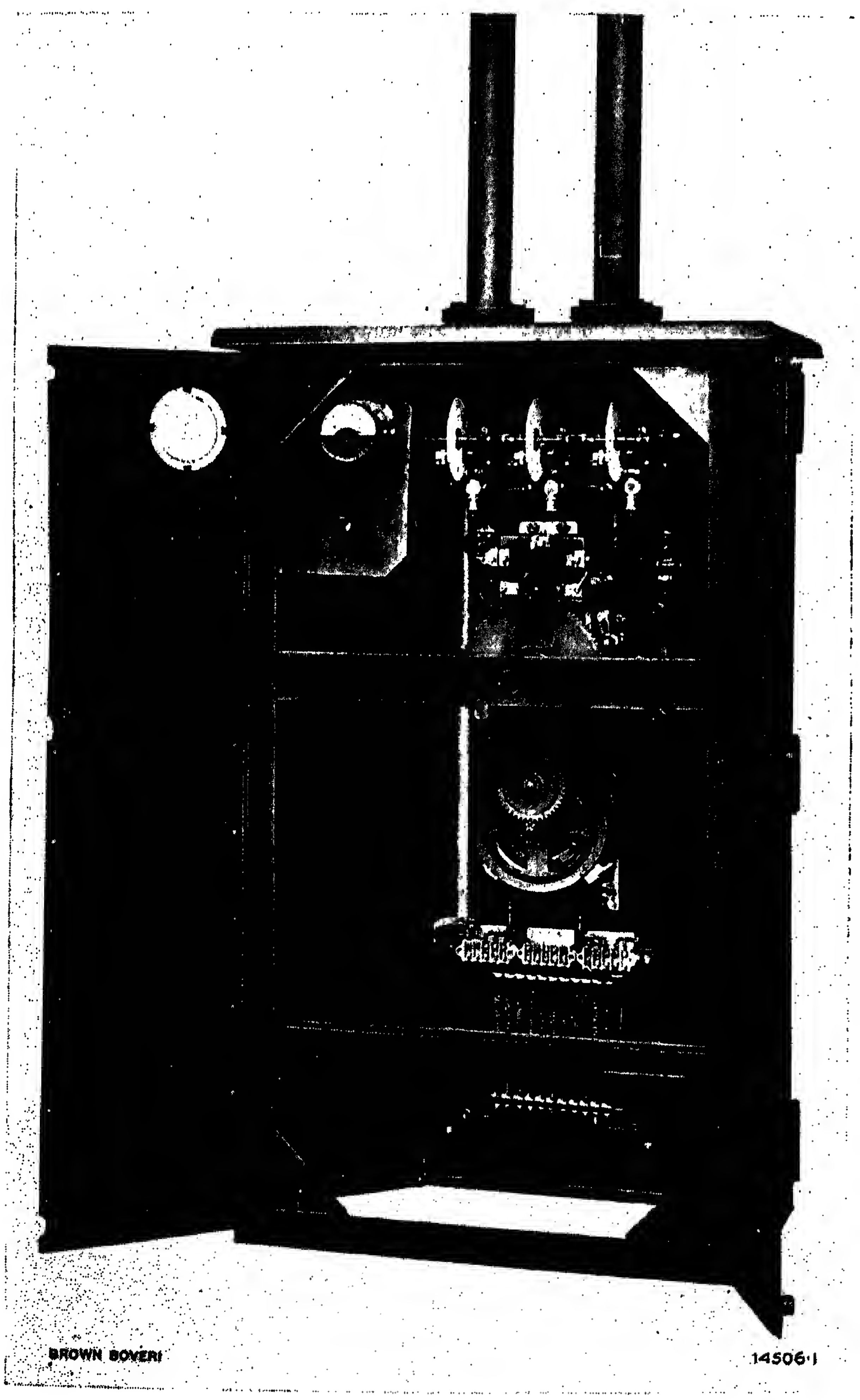


Fig. 15. — Interior mechanism of a control pillar for a set of three single-pole oil circuit breakers of outdoor type for 150'000 V.

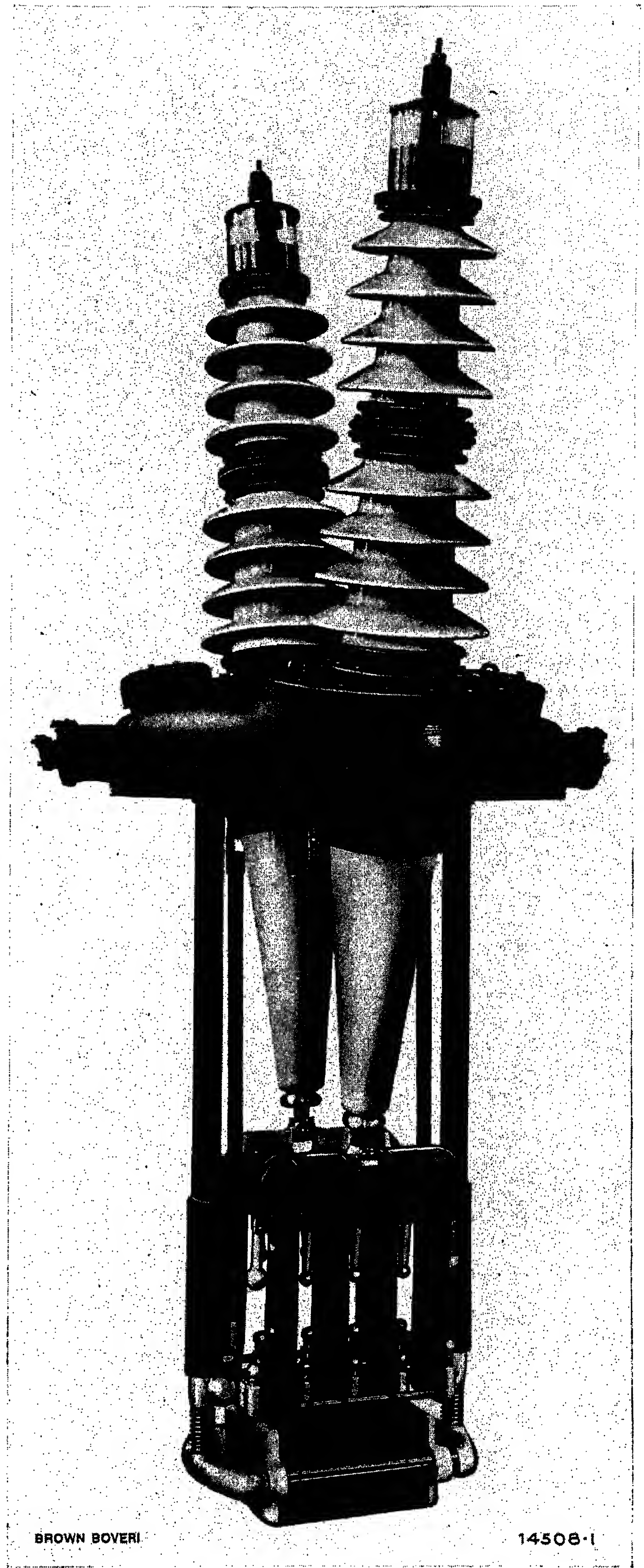


Fig. 16. — Single-pole oil circuit breaker of outdoor type, 150'000 V, 200 A, with tank removed. Below is a resistance for transformer protection, above which can be seen the contacts in the "open" position.

8. TESTS WITH LARGE SHORT-CIRCUIT LOADS.

(a) *Tests in Lœntsch Power Station.*

SOME years ago, a series of tests was made in the Lœntsch Station with a set of three single-pole oil circuit breakers, Type OE 30/400, for 27'000 V, 100 A. The design of this apparatus is no longer modern — in size it corresponds roughly to the present type A 12/1 for 35 kV. The alternator available for the tests had an output of 5250 kVA, 8000 V, 375 r. p. m., and was connected to a transformer for 8000/27'000 V. With the short circuits, the breaker was tripped by its own overload time-limit relay, which was set for minimum time lag. The apparatus was provided with a resistance for breaker protection, but the ohmic value of it was not the most suitable. The switching stages before and after the resistance had each two breaking points.

When the current was interrupted on a short circuit with a transformer tension of 31'500 V and about 600 to 900 A, the arc was found to be about 70 mm long, while there was not much smoke produced or oil thrown out. This short-circuit load represents about 32'000 to 50'000 kVA, three phase.

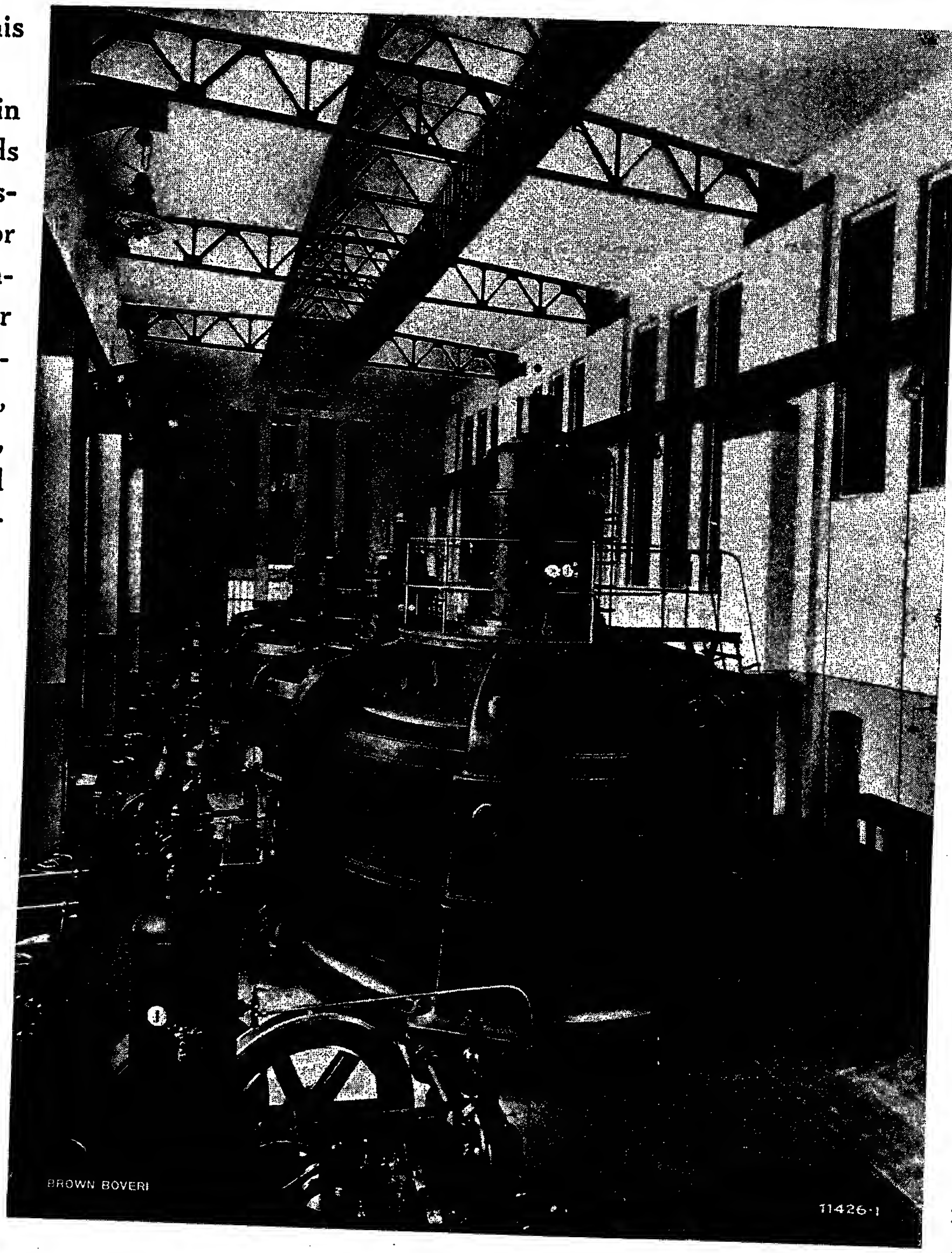


Fig. 17. — Machine room of Biaschina Power Station, Bodio (Switzerland). Three alternators of 8800 kVA each, one alternator of 14'600 kVA, 8000 V.

(b) *Tests in Biaschina Power Station, Bodio.*[1]

The tests in this station were made on a larger scale. The electrical data were recorded each time by two oscillographs, and the behaviour of the breaker was carefully observed.

The plant consisted of two alternators of 8800 kVA each, and one of 14'600 kVA, 50 cycles, so that the total power available was 32'200 kVA. The interior of this power station is shown in Fig. 17. For the tests, all three machines were run in parallel, or else only one used alone, and, in order to have the highest possible load on the switch, the current was always interrupted with the short-circuit peak load, and not on a sustained short circuit. To ensure this, the breaker was not tripped by an overload relay, whose operation would have had a certain time lag, but directly by means of the switch which was used to cause the short circuit. This enabled loads to be interrupted that corresponded to sustained short-circuit loads of a plant having three times the output. That is to say, when the three alternators were working in parallel, the circuit breaker dealt with a load of about the same value as would have to

[1] This plant was kindly placed at the disposal of Brown, Boveri & Co. by the Société Anonyme Motor for making short-circuit tests.

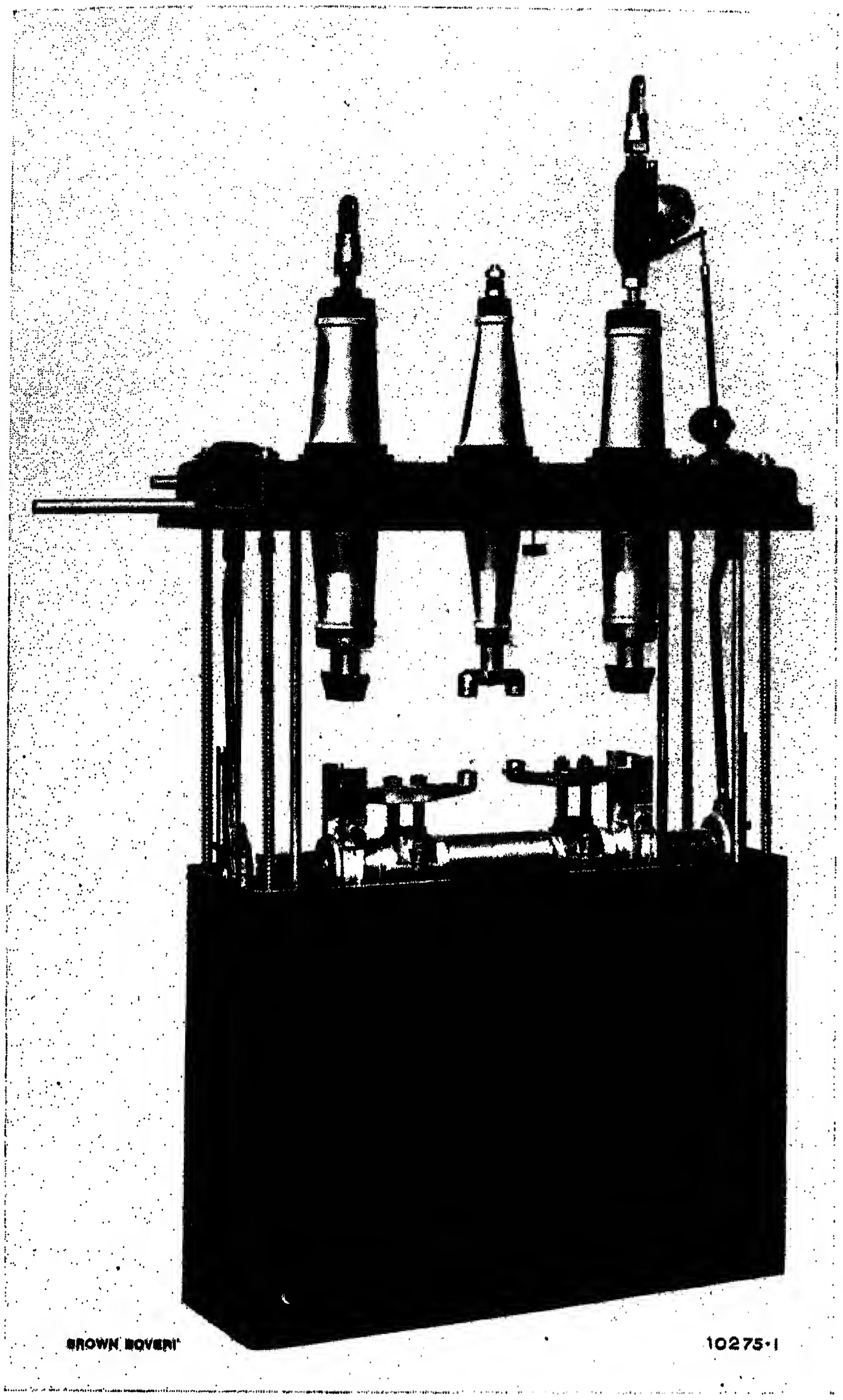


Fig. 18. — Single-pole oil circuit breaker, Type D 12/1 c, 35'000 V, 1000 A, with third bushing and built-on series time-limit relay.

be interrupted under regular working conditions in a station of 100'000 kVA when a short circuit took place.

The three circuit breakers employed for the tests were of the type D 12/1, and had each three bushings for 35'000 V. One of these breakers is shown in Fig. 18 with the tank lowered. There were normally four breaking points in each apparatus, and trials were made without protective resistances as well as with such accessories of different ohmic values. It was also possible to modify the circuit breakers in such a way that each one had 14 breaking points.

The comparative tests with different numbers of breaking points were carried out with one alternator at a reduced pressure of about 6000 V. The results obtained are given in the following table, which contains the average values of all the tests made.

Influence of the number of breaking points when rupturing the sudden short-circuit current of an alternator of 8800 kVA, 6000 V.

	No. of breaking points	
	4	14
Duration of arc in half-periods (50 cycles per second) . . .	6·9	3·25
Arcing energy . . . . kWsec	57	44
Approx. max. pressure impulses in the oil . . . . . . kg/cm^2	3·9	5·9
Noise produced	loud	moderate to weak
Production of smoke noticeable .	considerable	small
Speed of breaking at contact bar . . . . m/sec	0·94	0.72
Speed of breaking × number of breaking points	3·75	11·0

The oscillograms 84/25 a and b (Figs. 19 and 20) were made during one of the tests with each number of breaking points, the two oscillographs being coupled so that they worked in synchronism. The oscillograms (a) give the current and pressure at one pole of the circuit breaker being tested, while those marked (b) refer to the pressure impulses and the potential to earth in the same phase. The tension at the breaker is disturbed from the moment the arc is extinguished. This arises from the fact that the potential transformer used for measuring purposes then forms an oscillatory system in conjunction with the capacity of the line switched out.

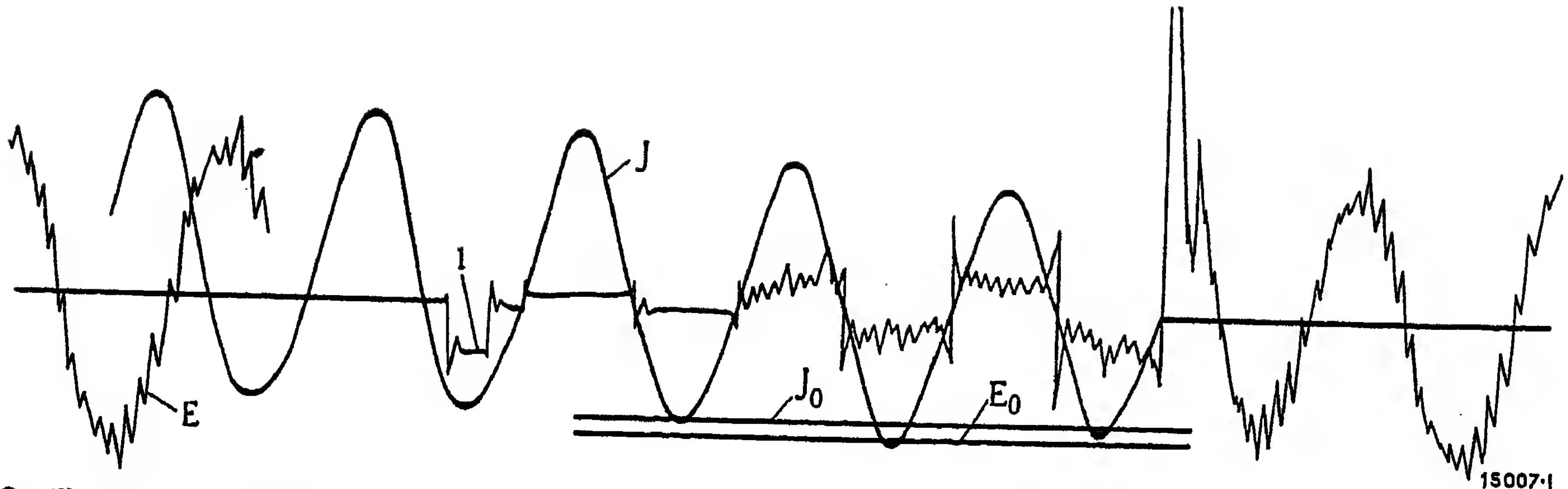
The instant the rupturing process begins is indicated by a mark on the curve giving the potential at the breaker.

The arcing energy was measured with the assistance of a ballistic wattmeter specially constructed for these tests. When the current and pressure coils of this instrument are connected to the switch through suitable measuring transformers, its needle moves at the moment of breaking by an amount representing the integral

$$\int e\, i\, dt$$

which is, therefore, proportional to the arcing energy.

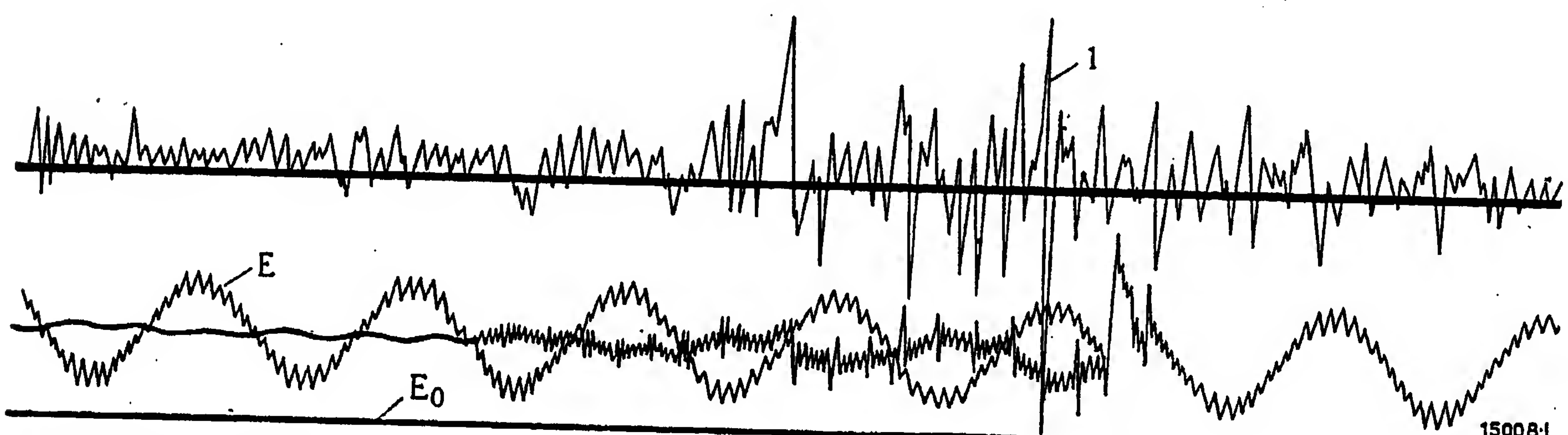
The pressure impulses in the oil were noted near the side of the tank by means of a special



Oscillogram No. 84/25 a.

Fig. 19. — Rupturing process when a circuit breaker with four breaking points is tripped during a short circuit; pressure 5800 V, alternator output 8800 kVA.

J. Short-circuit current.
E. Pressure at breaker in one phase.
J_0. Calibrating current, $J_0 = 2450$ A.
E_0. Calibrating pressure, $E_0 = 5900$ V.
1. Moment the contacts open.



Oscillogram No. 84/25 b.

Fig. 20. — Rupturing process when a circuit breaker with four breaking points is tripped during a short circuit; pressure 5800 V, alternator output 8800 kVA.

E. Potential of a phase to earth.
E_0. Calibrating pressure, $E_0 = 6250$ V.
1. Pressure impulses in the oil. (Approximate scale: 1 mm = 0·2 kg per cm².)

while the aggregate length of the different portions of the arc was increased by a quarter. These results correspond roughly to the conditions found during the tests with 700 kVA (see Fig. 7). They do not justify the construction of switches with such a large number of breaking points, especially as the arcing energy is only very slightly reduced, while the pressure impulses are more pronounced. This can be readily understood since the magnitude of the impulses is practically independent of the duration and length of the arc, whereas, with many breaking points, there are several arcs to cause pressure rises in the oil simultaneously.

The more or less favourable effect of the multiple breaks is undoubtedly dependent on the tension of

measuring apparatus which caused currents proportional to the oil pressure to flow, these currents being recorded by the oscillograph. This device did not operate entirely satisfactorily, so that the figures can only by taken as giving a rough idea of the magnitude of the impulses.

Attempts were also made to measure the volume of gas produced. For this purpose, a hood of suitable proportions made of bituba plates was placed in the oil just over the contacts of the breaker under observation. As the hood did not remain tight, due to the pressure waves in the oil, the data obtained are unfortunately not reliable.

The results of the tests may be summed up as follows:—

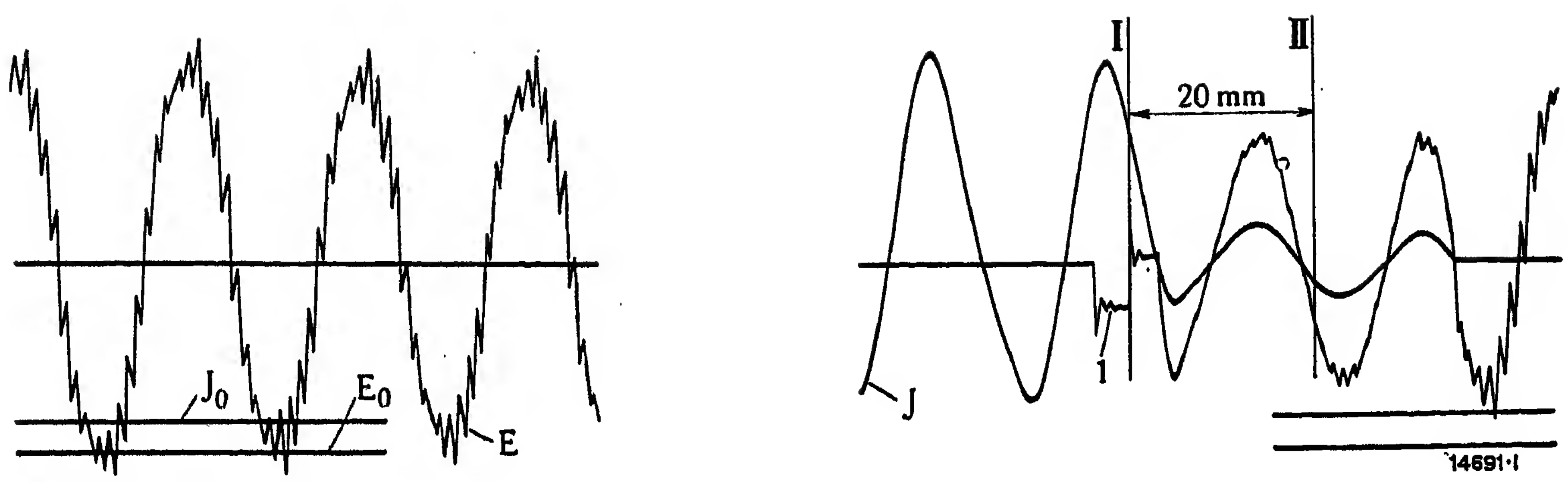
The observations made on the circuit breaker at Bodio showed quite a distinct improvement in the rupturing process when there was a large number of breaking points. The figures obtained in this respect were, however, not so favourable as had been anticipated: with $3^1/_2$ times as many breaking points, the duration of the arc was reduced by half,

the system to which the circuit breaker is connected, their adoption being all the more advantageous the higher the tension is. The results of the above series of tests lead to the conclusion that even with only 6000 V, the rupturing process is improved by the use of multiple breaks, and that with much higher pressures the effect may be expected to be correspondingly greater.

The results of the investigations made by Dr. Marguerre at Ryukanfos[1] agree with those obtained from the tests described above. Of the five circuit breakers of various makes which he employed, that furnished by Brown, Boveri & Co. had the largest number of breaking points, and was the only one that stood up to the duty required.

Even in earlier days, Brown, Boveri & Co. built with success oil circuit breakers having multiple contacts. Among these may be specially mentioned a large number of breakers, of a type now superseded, with 10 breaking points and only 5 cm closing distance, which have been in use nearly 12 years in a steam-turbine-driven central station, of more than 100'000 kVA capacity at 6000 V, in Buenos Ayres.

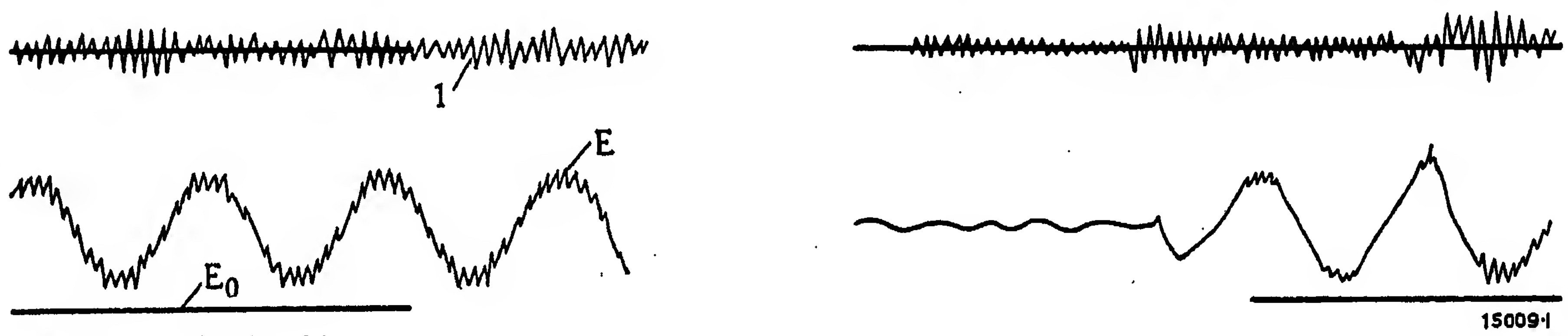
[1] Elektrotechnische Zeitschrift, 1912, p. 709.



Oscillogram No. 84/19a.

Fig. 21. — Rupturing process when a circuit breaker with two stages, each having two breaking points and a protective resistance of four times the short-circuit impedance, is tripped during a short circuit; pressure 5800 V, alternator output 8800 kVA.

J. Short-circuit current.
E. Pressure at breaker in one phase.
J_0. Calibrating current, $J_0 = 2670$ A.
E_0. Calibrating pressure, $E_0 = 7300$ V.
1. Moment the contacts open.
I, II. Moments the first and second stages open.



Oscillogram No. 84/19 b.

Fig. 22. — Rupturing process when a circuit breaker with two stages, each having two breaking points and a protective resistance of four times the short-circuit impedance, is opened during a short circuit; pressure 5800 V, alternator output 8800 kVA.

E. Potential of a phase to earth.
E_0. Calibrating pressure, $E_0 = 7150$ V.
1. Pressure impulses in the oil. (Approximate scale: 1 mm = 0·1 kg per cm².)

With these circuit breakers there has never been the least trouble.

The tests to determine the effect the use of resistances for protecting the breaker has on its rupturing capacity were also made with a pressure of 6000 V and short circuits with one alternator. Three different sizes of resistances were employed, whose ohmic values were equal to 1, 4, and 8 times the short-circuit impedance of the alternator. The apparatus had two breaking points in each switching stage.

The oscillograms 84/19a and b (Figs. 21 and 22) show the rupturing conditions when using a resistance corresponding to four times the impedance. The arc at stage I lasted 0·4, and that at stage II, 1·8 half-periods.

The average values of the results obtained are given in the following table, which also contains those got from the same circuit breaker when employed with four breaking points and no resistance.

Effect of a resistance for breaker protection when rupturing the instantaneous short-circuit current of an alternator of 8800 kVA, 6000 V.

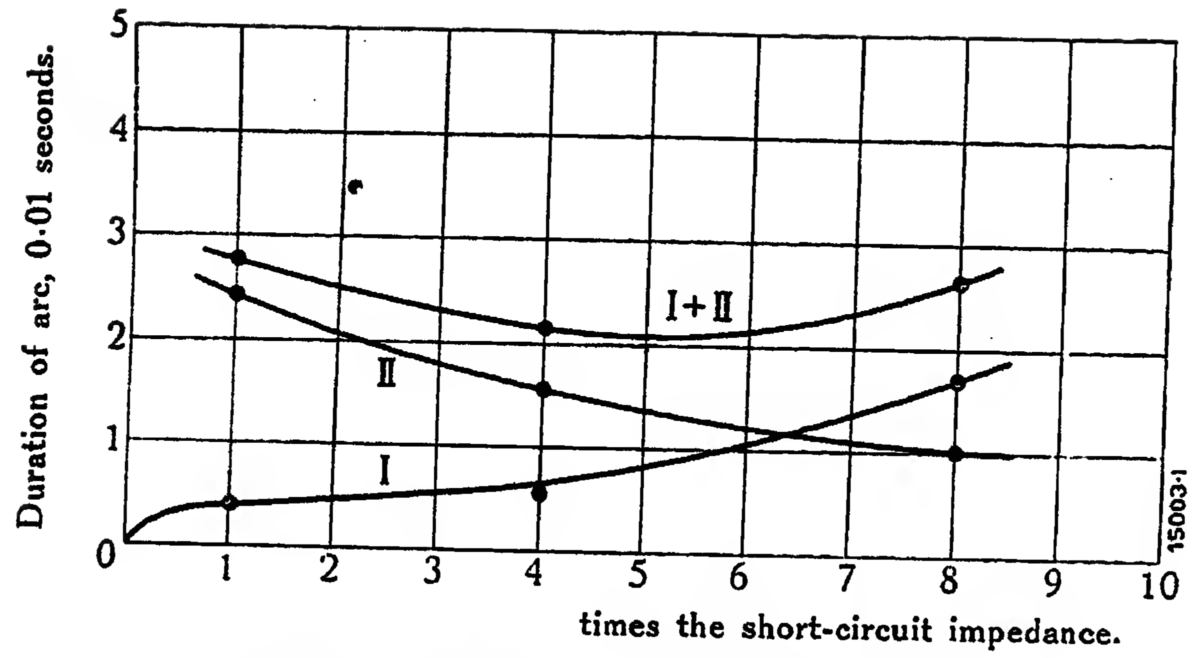
	Resistance			
	0	1	4	8
	times the short-circuit impedance of the alternator			
Duration of arc in half-periods (50 cycles), stages I and II	6·9	0·33+2·4	0·6+1·5	1·65+1·0
Sum of I and II		= 2·73	= 2·1	= 2·65
Arcing energy for the two stages kW sec	57	50	25	5·5
Max. pressure impulses in the oil . kg/cm²	3·9	0·65	0·27	0·25
Approx. volume of gas cm³	150	35	32	37
Noise produced	loud	←— very weak —→		

When comparing the different periods the arc lasted, it must be remembered that without resistances there were arcs at four contacts, whereas with resistances, arcs are struck at only two contacts. The total duration of the arc must be divided by two in order to obtain the average time for each stage. The arcing energy at the two stages was determined as follows:— The energy absorbed by the resistance was calculated, and subtracted from the reading of the ballistic wattmeter, which corresponded to the total energy in the resistance and breaker together. The measurement of the quantity of gas generated was reliable when using a resistance, as the collecting hood was not affected by the very slight impulses produced in the oil.

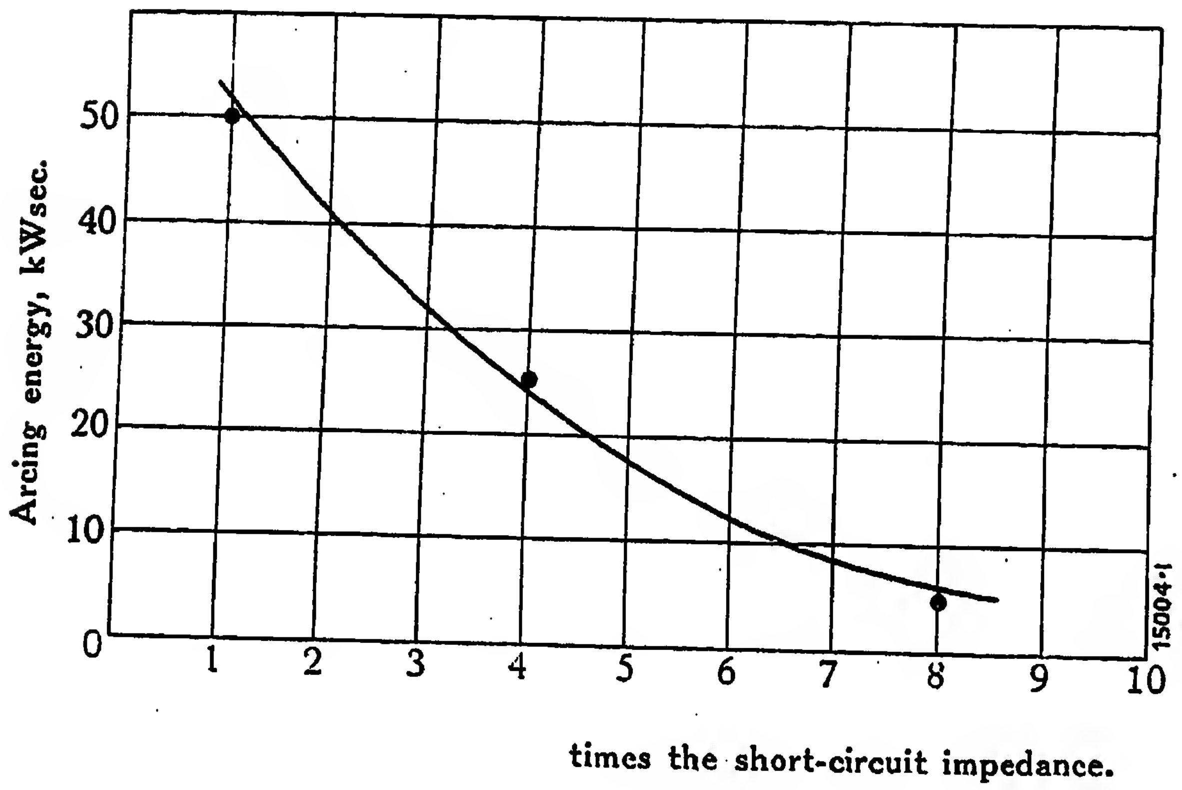
Curves showing the duration of the arc, the arcing energy and the value of the pressure impulses are given in Figs. 23, 24 and 25.

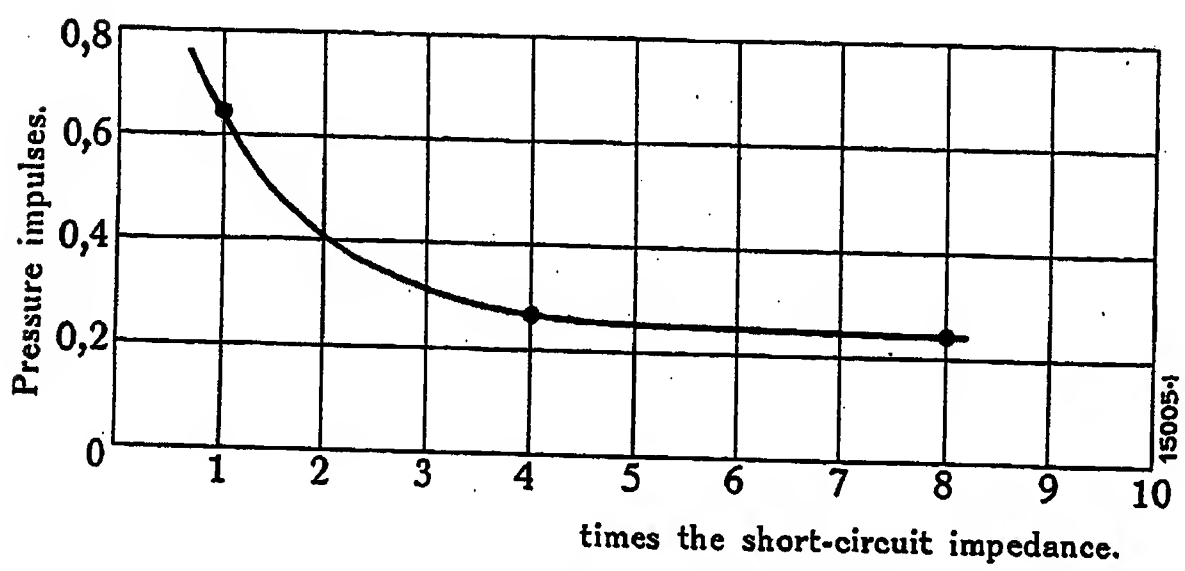
Conclusions. From these curves, it can be seen that neither the pressure impulses nor the arcing energy, which is the most important factor, reach their minimum value with the largest resistance used during the tests. It would appear that a resistance equal to about *10 times the short-circuit impedance is the most favourable amount,* but that this figure need not be rigidly adhered to.

The results also give an idea of the increase possible in the rupturing capacity by providing a



I. Stage I. II. Stage II. I + II · Sum of I and II.





Figs. 23, 24, 25.
Duration of arc, arcing energy and pressure impulses when rupturing a three-phase short-circuit load of about 26'000 kVA at 6000 V.

resistance for the circuit breaker. As compared with an apparatus without such a resistance, the improvement can be taken to be roughly as follows:— The duration of the arc falls to $^1/_4$, the arcing energy to $^1/_{10}$, the pressure impulses to $^1/_{15}$, and the volume of gas to $^1/_5$ when a resistance is employed. It can therefore be assumed, with sufficient accuracy, that *a circuit breaker with a resistance has four times the breaking capacity* of the same apparatus without it.

Tests with the alternator of 14'600 kVA, at about 8000 V (with full excitation) gave the following average results with multiple breaks and no resistance:

Duration of arc in half-periods (50 cycles)	5·5
Arcing energy	130 kWsec
Approx. max. pressure impulses . .	4·3 kg/cm^2

The conditions during one of these tests can be seen from the oscillograms 84/35 a and b in Figs. 26 and 27. There was a fair amount of oil thrown out, and quite a large quantity of gas produced. Judging from experience, however, it seemed that the full breaking capacity of the apparatus had not nearly been reached. This is confirmed by the length of the arc, which measured only about 4 cm, whereas a length of about 10 cm is allowable with the breaker in question.

The oscillogram 84/37 a and b (Figs. 28 and 29) show what took place when the momentary short-circuit current of all three alternators running in parallel was interrupted. The tension at the very end of the rupturing process is not given in these diagrams. From the data obtained, it can be concluded that the length of the arc was in the neighbourhood of 6 cm, i. e., still considerably below the maximum length of 10 cm allowable. The figure for the pressure impulses in the oil was only about 3·5 kg per cm^2. From all the tests made, it did not appear to rise with increasing loads.

In all, about 40 sudden short circuits were made with the various machines, which were not harmed in the slightest by the strenuous requirements they were called upon to meet.

(c) *Tests with a 12'000-kVA turbo-alternator.*

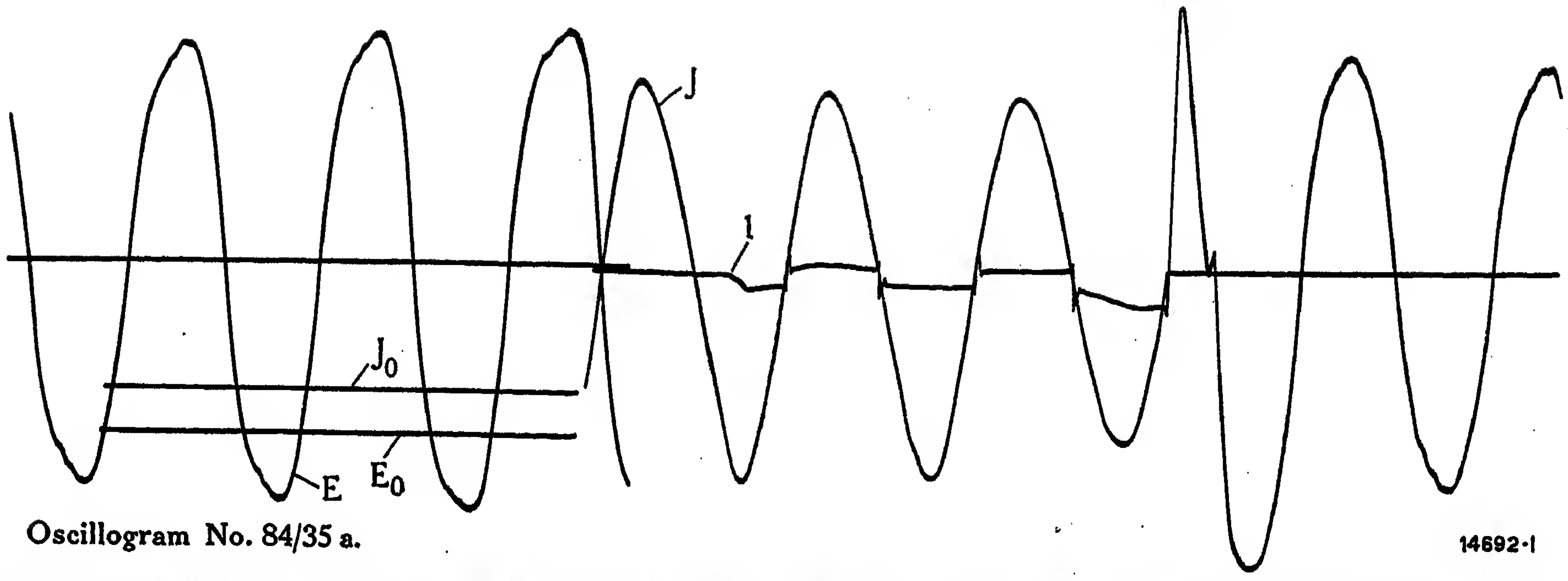
This machine is shown in Fig. 30 as erected in the turbine testing department of Brown, Boveri & Co. for making short-circuit tests. Its speed is 3000 r. p. m., the tension 11'000 V, and the frequency 50 cycles. As the foundation was not considered substantial enough, the set was specially clamped down to withstand the sudden stresses accompanying the short circuits. The piping visible in the illustration was provided for the purpose of admitting steam to the alternator in the event of a fire starting there.

Three different types of oil circuit breakers were tested, namely:—

I. A single-pole breaker for 35'000 V, 600 A with six breaks, but no protective resistance.

II. A standard triple-pole breaker, Type A 8/3, for 12'000 V, 200 A, as shown in Fig. 1.

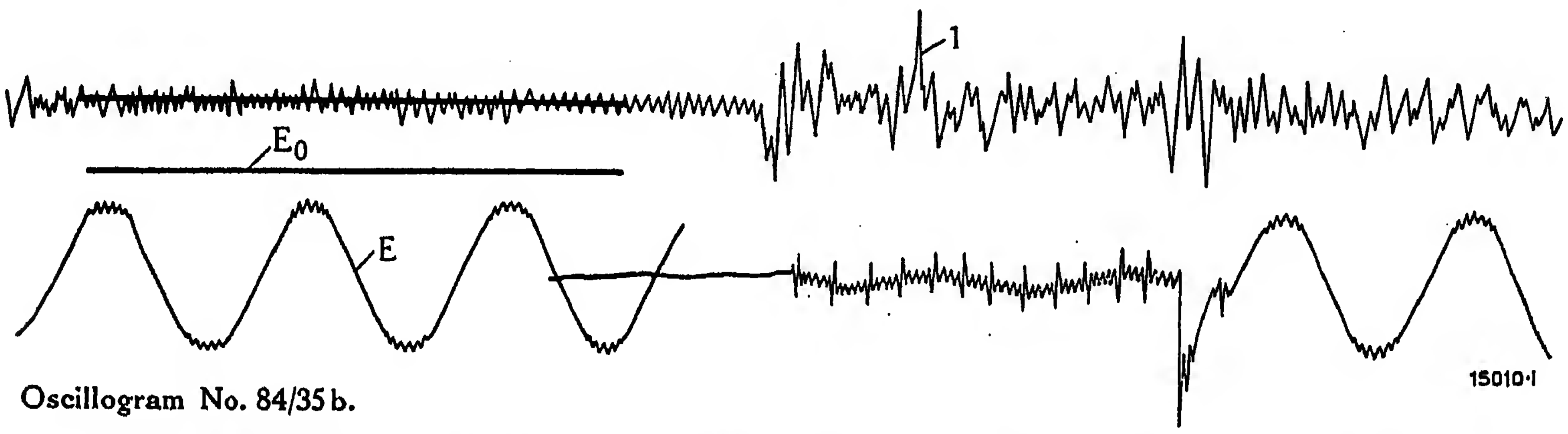
III. Three single-pole breakers, as used on the Gothard locomotives, for 15'000 V, 350 A, with a resistance for transformer protection (Figs. 33 and 34).



Oscillogram No. 84/35 a.

Fig. 26. — Rupturing process when a circuit breaker with fourteen breaking points is tripped during a short circuit; pressure 8100 V, alternator output 14'600 kVA.

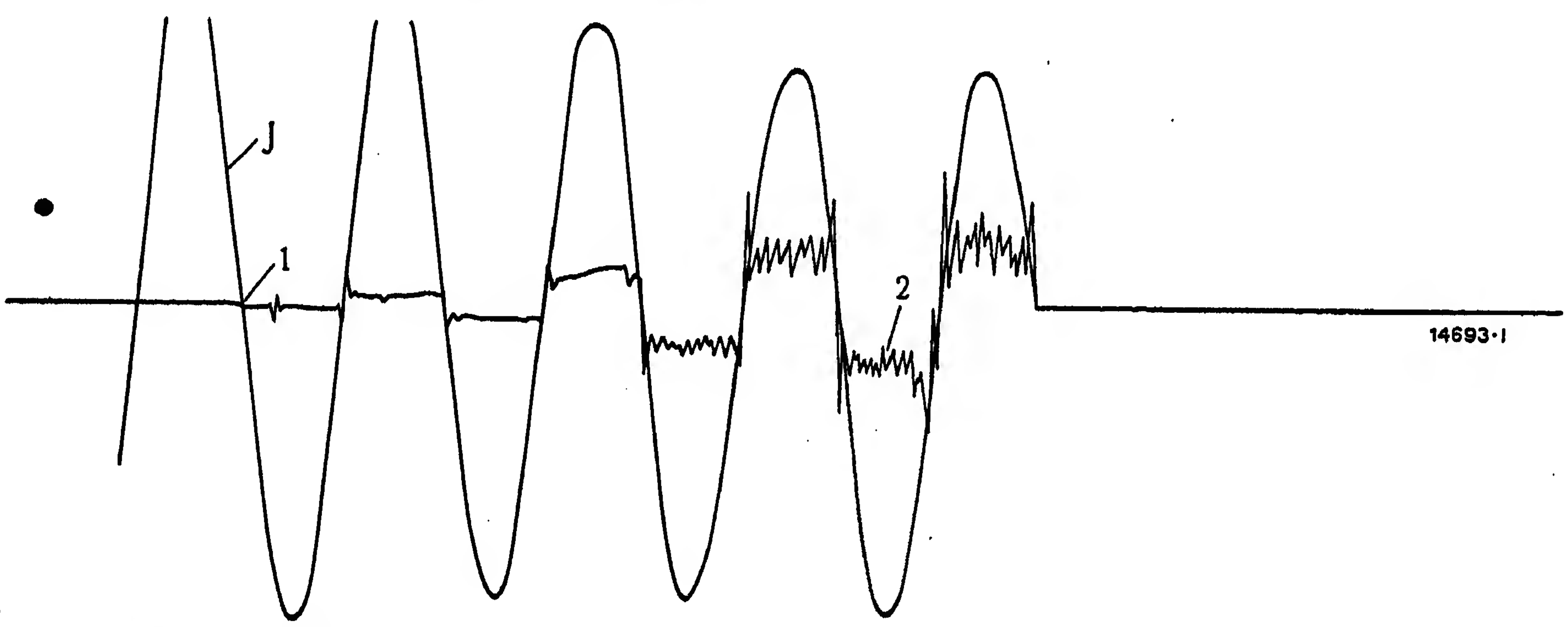
J. Short-circuit current. J_0. Calibrating current, $J_0 = 4930$ A. 1. Commencement of the arc.
E. Pressure at breaker in one phase. E_0. Calibrating pressure, $E_0 = 6650$ V.



Oscillogram No. 84/35 b.

Fig. 27. — Rupturing process when a circuit breaker with fourteen breaking points is opened during a short circuit; pressure 8100 V, alternator output 14'600 kVA.

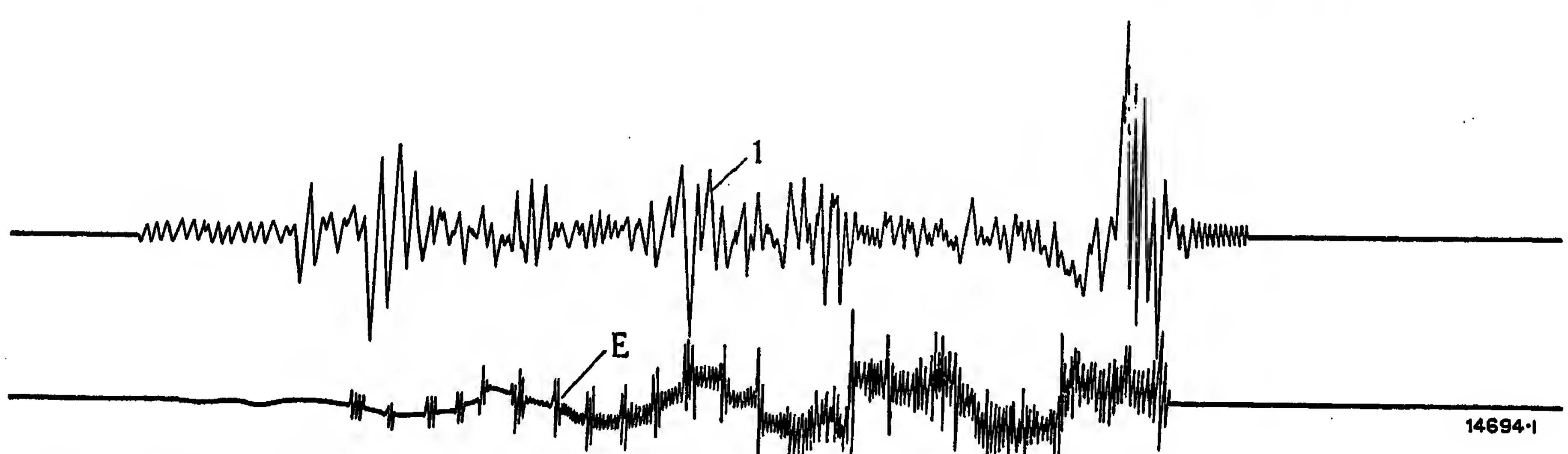
E. Potential of a phase to earth. E_0. Calibrating pressure, $E_0 = 9000$ V. 1. Pressure impulses in the oil. (Approximate scale: 1 mm = 0·5 kg per cm².)



Oscillogram No. 84/37 a.

Fig. 28. — Rupturing process when a circuit breaker with fourteen breaking points is opened during a short circuit; pressure 7750 V, aggregate output of the three alternators 32'000 kVA.

J. Short-circuit current. 1. Commencement of the arc. 2. Tension across the arc.



Oscillogram No. 84/37 b.

Fig. 29. — Rupturing process when a circuit breaker with fourteen breaking points is opened during a short circuit; pressure 7750 V, aggregate output of the three alternators 32'200 kVA.

E. Potential of a phase to earth. 1. Pressure impulses in the oil. (Approximate scale: 1 mm = 0·5 kg per cm².)

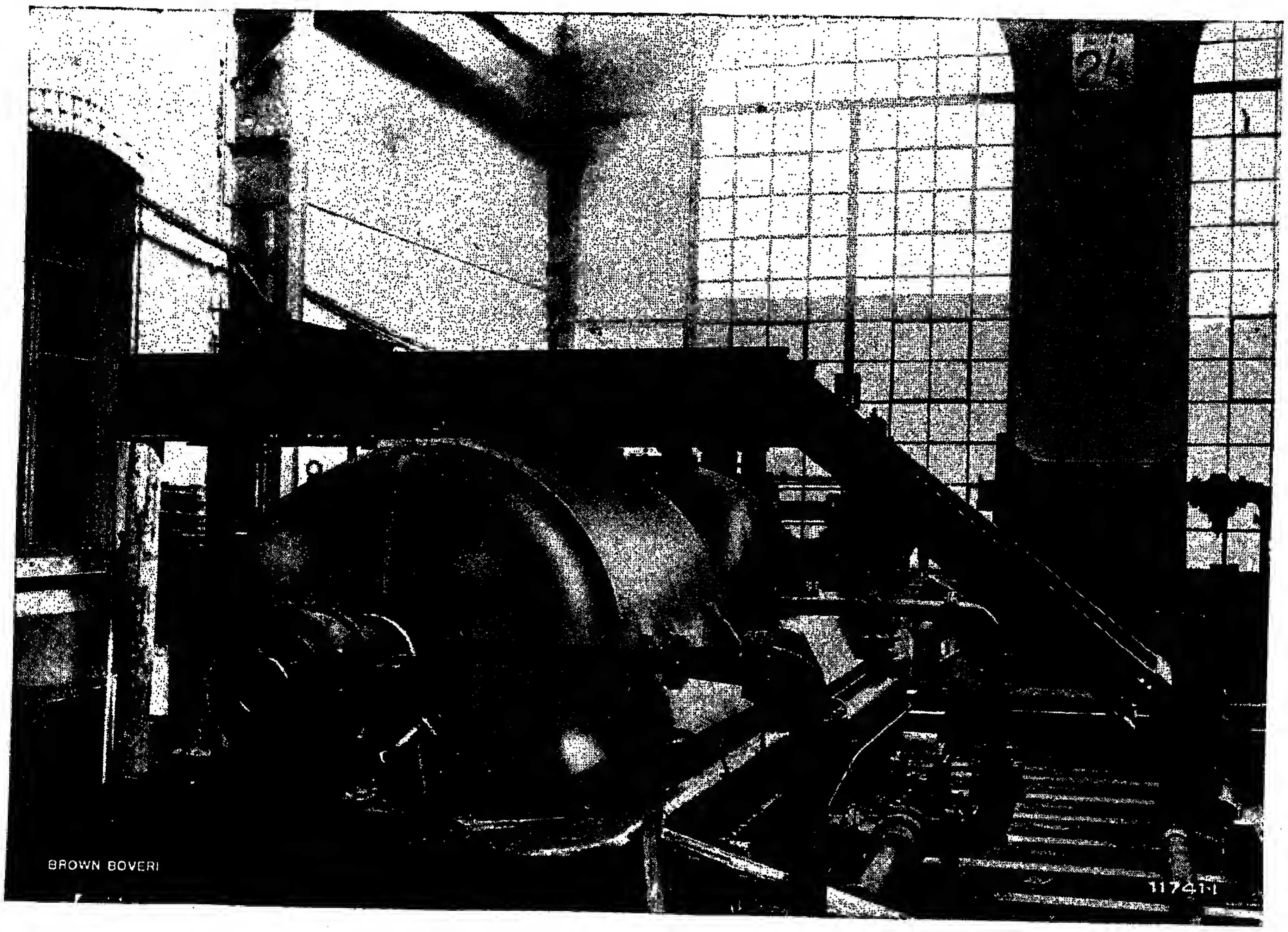


Fig. 30. — Turbo-alternator, 12'000 kVA, 11'000 V, 3000 r. p. m., as used for short-circuit tests in Baden works, Brown, Boveri & Co.

Tripping took place in all cases without time lag, so that the duty corresponded to the conditions met with in normal service in a generating plant having several times the output of that used for the tests in question.

Some of the tests were made with three-phase, and others with single-phase current. In a number of cases, the alternator was delta connected with a normal pressure of 6400 V, and this permitted very high short-circuit currents (up to 33'000 A, peak value) to be reached. The duty required of the breaker was then heavier than with a lower current at a correspondingly higher tension.

The following tests were made on all three circuit breakers:—

1. The current was passed through the apparatus without its tripping.
2. The breaker was closed on a short circuit without tripping immediately after.
3. The short-circuit current was interrupted by the breaker.
4. The breaker was reclosed on the short circuit and allowed to trip again.

I. Tests on a single-pole circuit breaker for 35'000 V. This apparatus was closed and tripped about 15 times. The oscillograms 111/7 and 111/9 (Figs. 31 and 32) refer to two of these tests. In the latter figure, which shows the conditions at closing and opening instantaneously with a pressure of 3500 V, the values of the current, etc. are as follows:—

Maximum peak current	22'500 A.
R. M. S. current while rupturing . .	10'000 A.
Three-phase load while rupturing .	160'000 kVA.

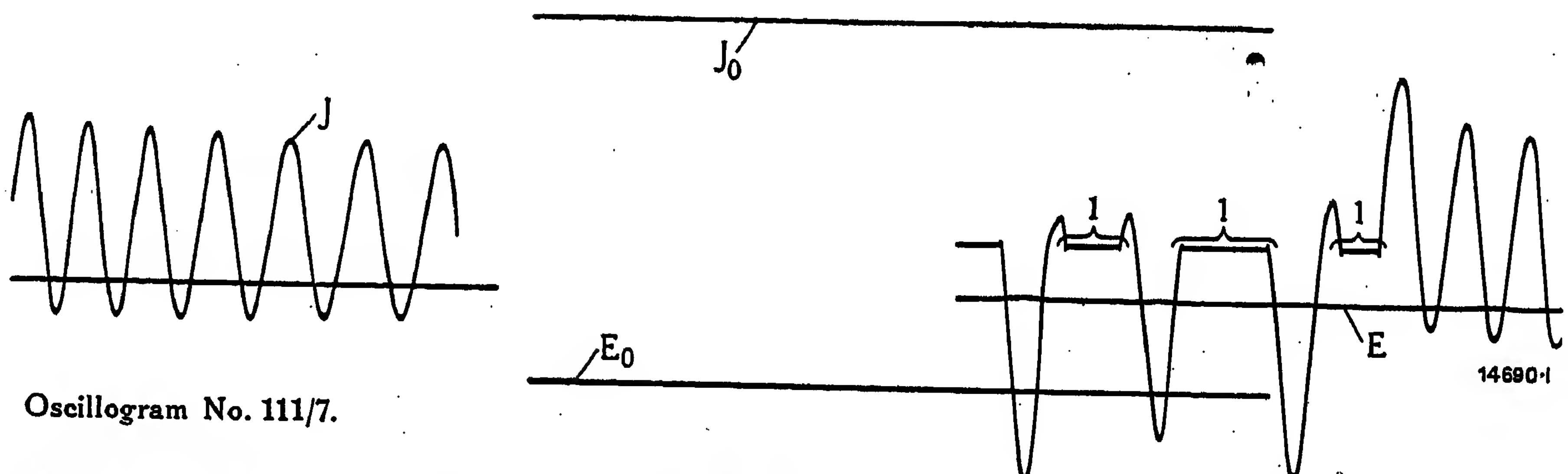


Fig. 31. — Closing on a short circuit with a 35'000-V oil circuit breaker; alternator output 12'000 kVA.

J. Short-circuit current.
E. Pressure at breaker.
J_0. Calibrating current, $J_0 = 21'300$ A.
E_0. Calibrating pressure, $E_0 = 3040$ V.
1. Interruption of current due to contacts parting.

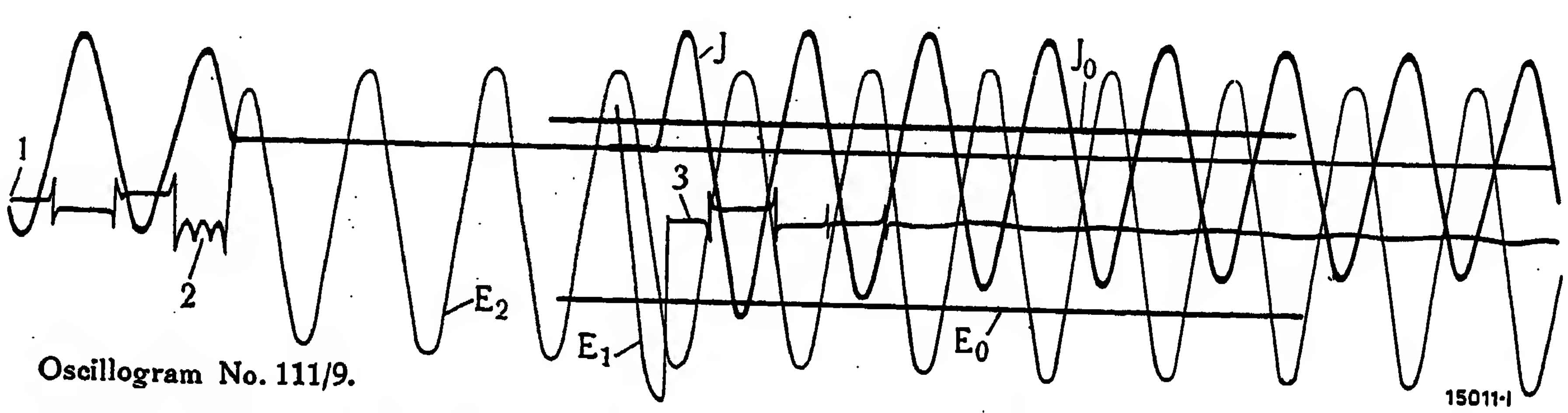


Fig. 32. — Closing and opening on a short circuit with a 35'000-V oil circuit breaker; alternator output 12'000 kVA.

J. Short-circuit current.
E_1. Pressure before short circuit.
E_2. Pressure after rupturing.
J_0. Calibrating current, $J_0 = 3900$ A.
E_0. Calibrating pressure, $E_0 = 3100$ V.
1. Commencement of the arc.
2. Tension across the arc while rupturing.
3. Tension across the arc when closing the breaker.

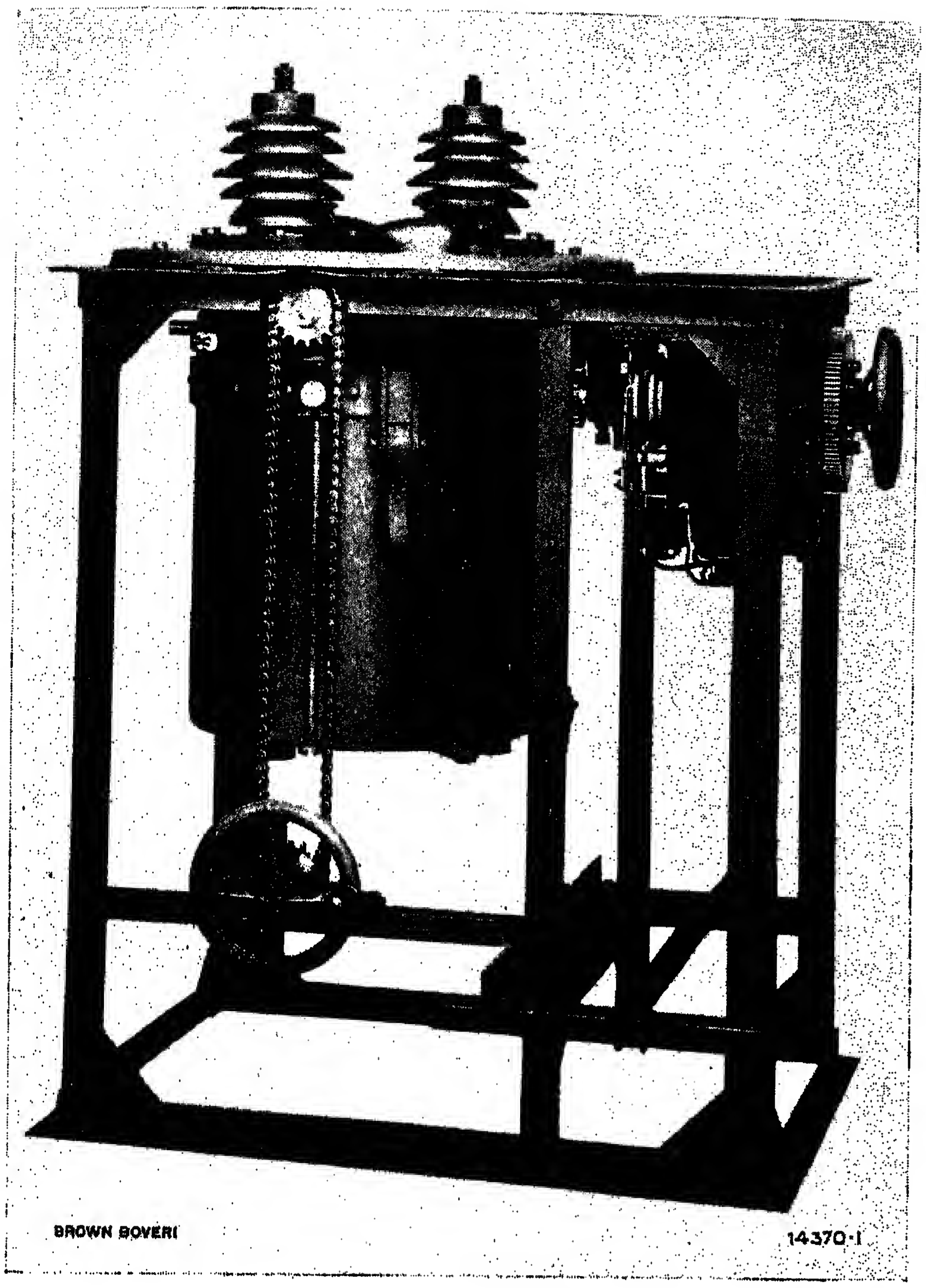


Fig. 33. — Single-pole oil circuit breaker for electric locomotives, 15'000 V, 350 A, with motor control, built-in current transformer, and resistance for transformer protection, mounted on a frame for testing purposes.

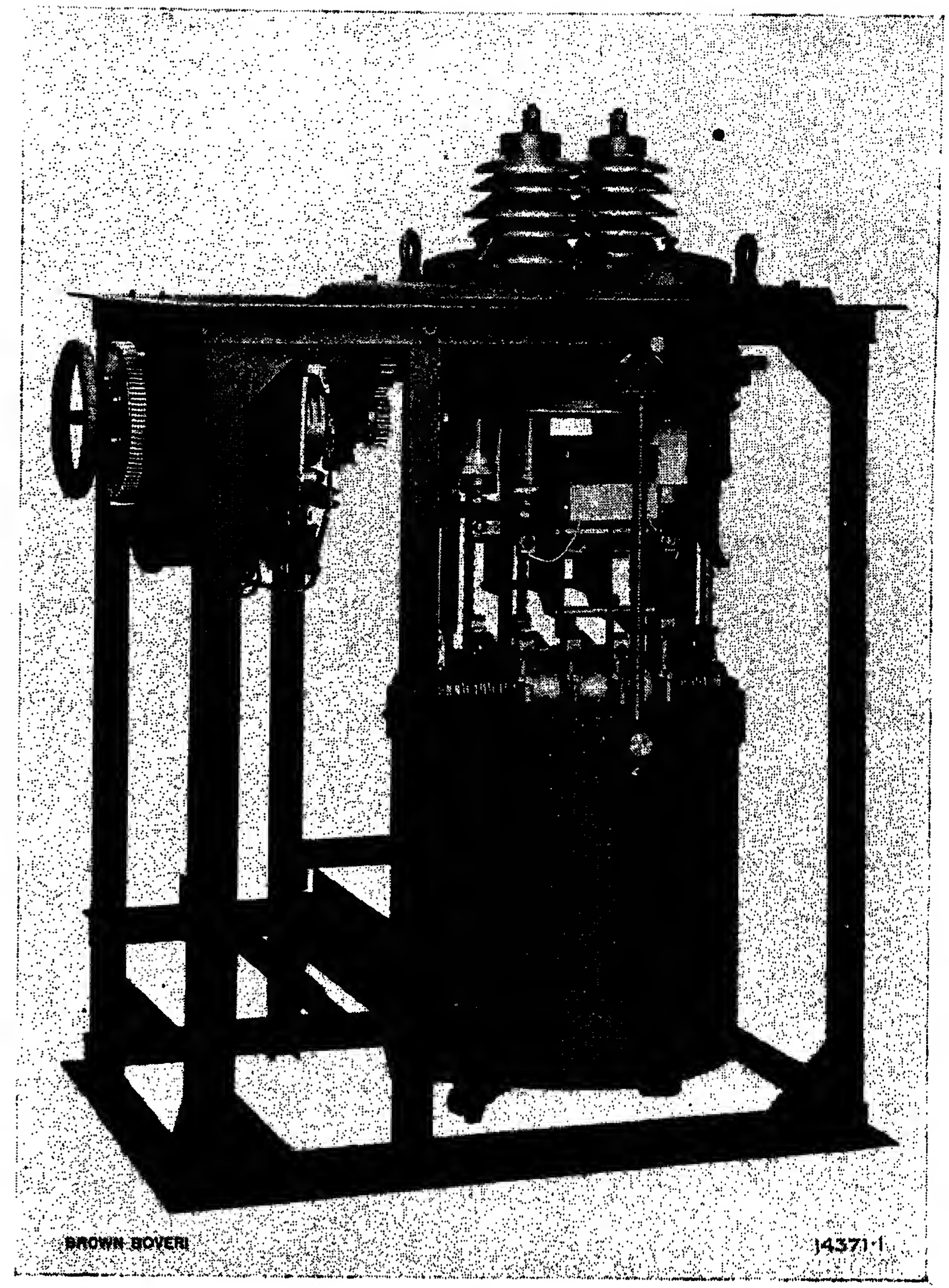


Fig. 34. — Same circuit breaker as in Fig. 33 with oil tank lowered.

Duration of arc in half-periods
(50 cycles) 4
Arcing energy . . . . 400 kWsec.

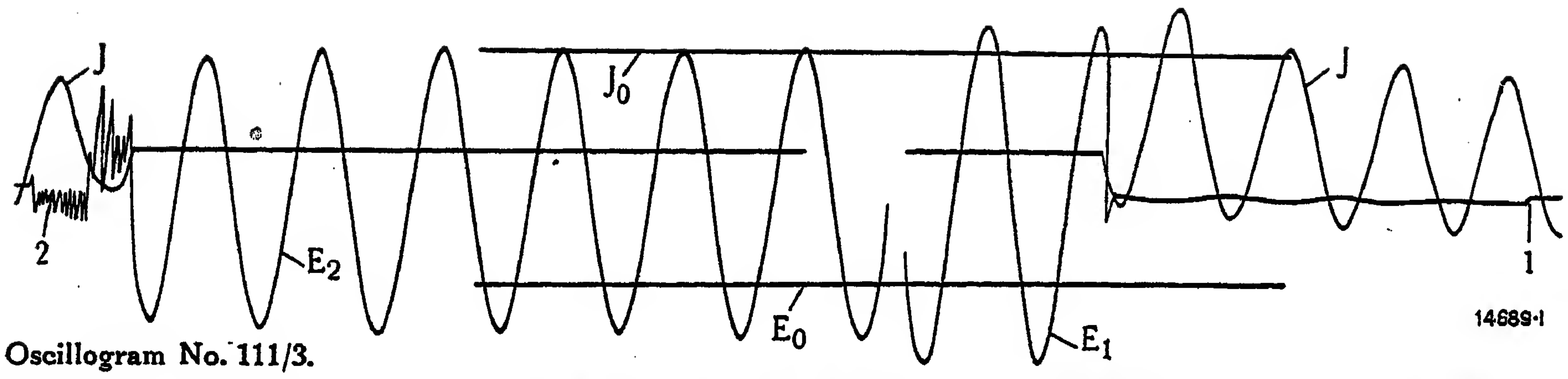
The length of the arc was only 3·5 cm. There was no excessive burning of the contacts, and the circuit breaker was still entirely serviceable at the conclusion of the tests.

The contacts first employed in this apparatus were found to have been separated by the electrodynamic forces resulting from the high currents. This effect was at times so great that when the breaker was closed on a short circuit, the current was actually interrupted again by the contacts coming apart. The latter occurrence is noticeable in the oscillogram 111/7 (Fig. 31). For this test, the operating gear of the circuit breaker was adjusted in such a way that the main contacts did not touch, and the instantaneous short-circuit current was found to have been interrupted three times within 6 periods. The maximum peak value of the current was 25'000 A. When switched in on the short circuit (without immediately opening again), there was a distinct shock, expulsion of oil, and smoke, just as when interrupting a very heavy overload. In consequence of the arc formed through the contacts separating, some of the latter were fused together.

The experience made with this apparatus led to the design of a modified arrangement of contacts which was subsequently fitted to it.

II. Tests on a triple-pole circuit breaker, Type A 8/3, for 12'000 V. Among the tests made with this breaker were several in which it was closed and opened instantaneously with a three-phase load of about 120'000 kVA, 10'300 V, 6600 A. This heavy duty did not damage it in the slightest nor lessen its serviceableness. There was, however, a good deal of smoke, considerable throwing out of oil, and at times flames were also noticeable.

During these tests, the breaker had neither an insulating lining for the tank, nor insulating plates between the contacts of the different phases.



Oscillogram No. 111/3.

Fig. 35. — Closing and opening on a short circuit with an oil circuit breaker for locomotives; alternator output 12'000 kVA.

J. Short-circuit current.
E_1. Pressure before short circuit.
E_2. Pressure after rupturing.
J_0. Calibrating current, $J_0 = 20'500$ A.
E_0. Calibrating pressure, $E_0 = 3060$ V.
1. Commencement of the arc.
2. Tension across the arc.

III. Tests on an oil circuit breaker as used for locomotives. The apparatus experimented upon in this case had a cylindrical, explosion-proof tank with a very substantial fixing device, insulating plates between the contacts, and also an insulating lining for the tank. The contacts were forced apart at first in this breaker too, but it was possible to overcome this effect by suitably modifying their arrangement. A series of switching-in and switching-out tests were made with pressures up to about 5500 V. Oscillogram 111/3 (Fig. 35) refers to one of these trials. The pressure here was 5500 V, the values of the current, etc. being the following:—

Maximum peak current about	30'000 A.
Current while rupturing	12'200 A.
Three-phase load while rupturing	200'000 kVA.
Duration of arc in half-periods (50 cycles) .	3
Arcing energy . . .	250 kWsec.

On every occasion, the various phenomena accompanying the operation of the circuit breaker did not exceed the permissible values. Its condition always remained such that it could be used again for regular service without overhauling, and there was so little burning of the contacts that these did not even require touching up.

(d) Testing an oil circuit breaker as used for locomotives with single-phase current, $16^2/_3$ cycles.

An important foreign electric railway had tests made in a substation on circuit breakers of various makes destined for use on the locomotives. The apparatus furnished by Brown, Boveri & Co. was of the same design as the one with which the tests described in section 8 c, III were made (see Figs. 33 and 34). The substation in question contained three transformers of 1600 kVA each, 80'000/15'000 V. These are fed from a power station with turbo-generating plant of 15'000 kVA through a double transmission line having a length of 40 km, and a very small pressure drop.

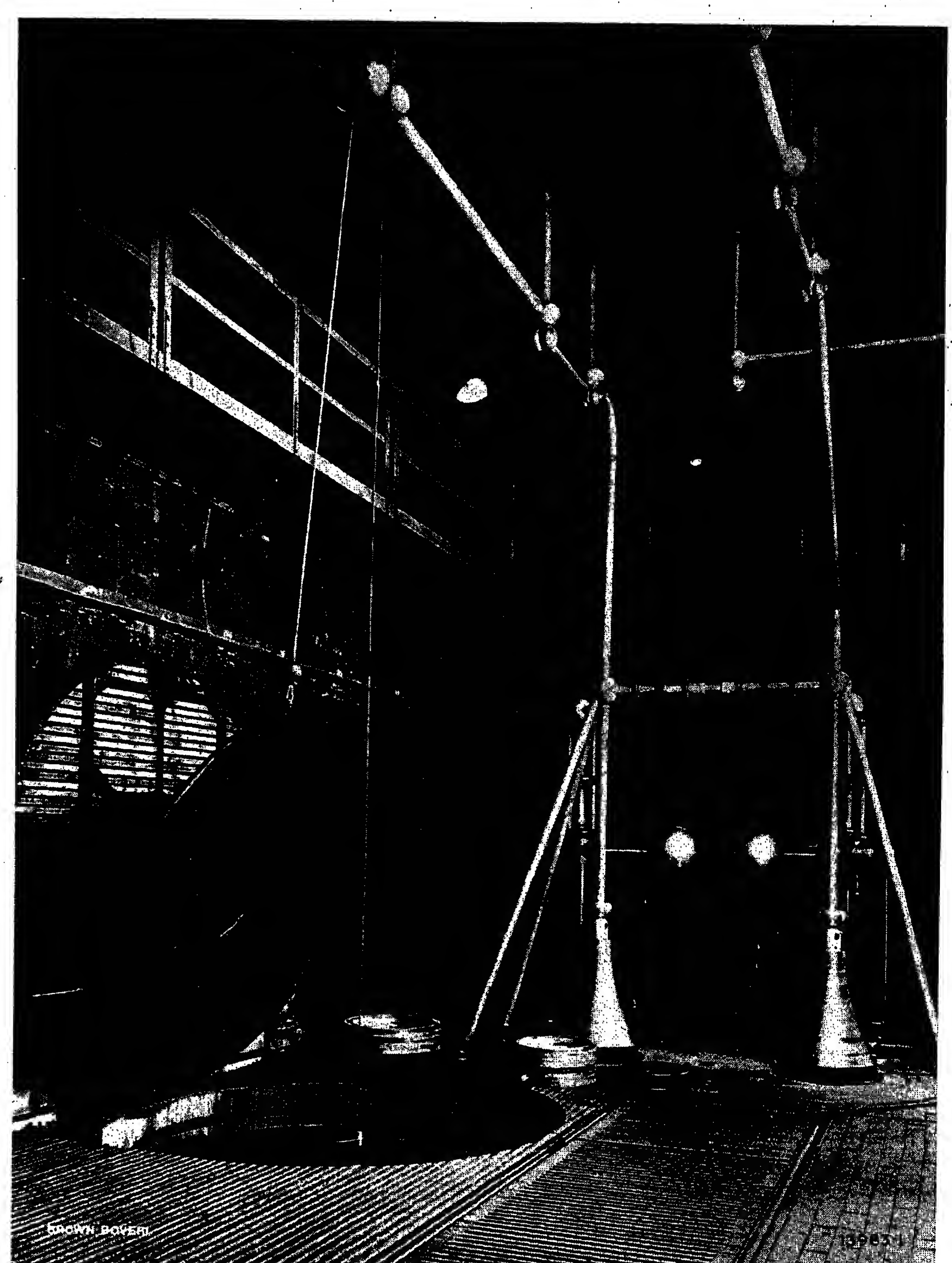


Fig. 36. — High-tension testing department, Brown, Boveri & Co., Baden.

The following tests were made:—

1. The short-circuit current was passed through the breaker; this had no noticeable effect.

2. The breaker was tripped by the short-circuit current with the relay set for opening instantaneously. The current was interrupted in this manner five times at intervals of one to four minutes. There was considerable vibration of the whole apparatus (which was mounted on a light framework), small puffs of smoke were expelled through the expansion valves, no oil was thrown out, the contacts were only slightly burned, and all parts remained perfectly intact.

3. The breaker was closed and allowed to trip instantaneously. This was done three times at intervals of one minute, the result being the same as with test 2.

In all cases, the circuit breaker was still in perfect working condition after the tests. The amount of burning at the contacts was so small that the apparatus could have been used for several times as many switching operations without requiring any attention.

The pressure for these experiments was 16'000 V, and the current while interrupting rose as high as 3250 A, which corresponds to a three-phase load of 155'000 kVA.

The Brown Boveri circuit breaker was the only one that stood up satisfactorily to several repetitions of this heavy duty — the breakers of other makes being all rendered unserviceable during the first trials. As a result, the Brown Boveri locomotive-type oil circuit breaker was adopted as standard by the railway in question for use on all the locomotives of various designs running on its system. The Swiss Federal Railways have also decided to instal the same type of Brown Boveri circuit breaker on all their electric locomotives, no matter by what firm the latter are supplied.

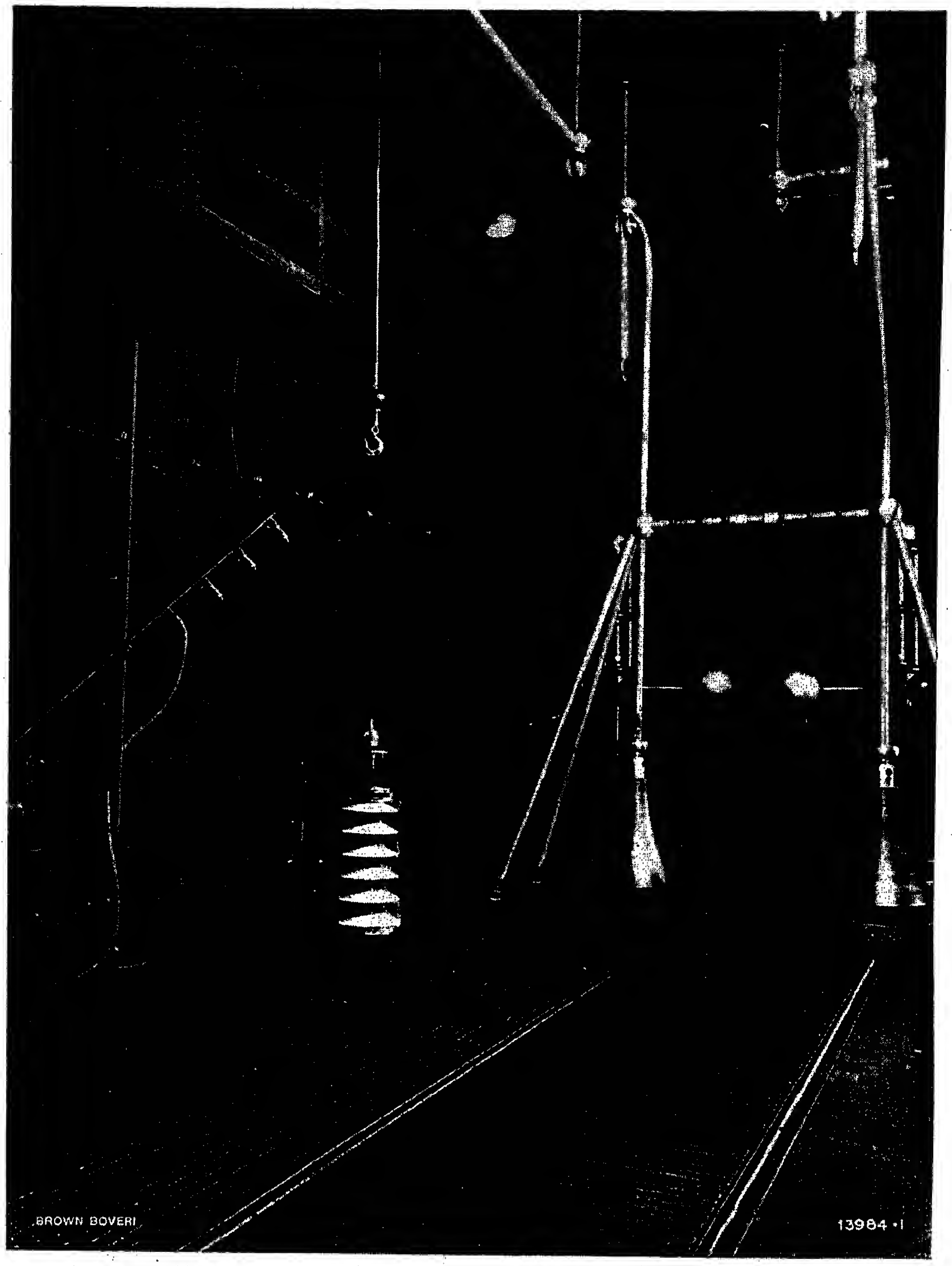


Fig. 37. — Flashover test on an oil-filled bushing for 110'000 V in the high-tension testing department, Brown, Boveri & Co., Baden.

9. METHODS OF MOUNTING OIL CIRCUIT BREAKERS.

(a) In buildings.

The practice of dividing up switch rooms into single cells, each containing a set of switches, increases the safety of the installation, and is one that should always be followed in order to lessen the possibility of disturbances.

Even with circuit breakers that can interrupt the maximum short-circuit load with perfect safety, there is still the possibility of fires due to burning oil or explosions to be reckoned with. Such disturbances can arise from causes of quite secondary importance: main contacts in a bad state of repair may become overheated, and lead to ignition of the oil under certain circumstances; flashovers in the apparatus may result from water affecting the insulation or from a deposit of dust on the latter. Explosions can also be produced by the gases liberated when rupturing a normal short circuit becoming ignited due to some cause not directly connected with the circuit breaker.

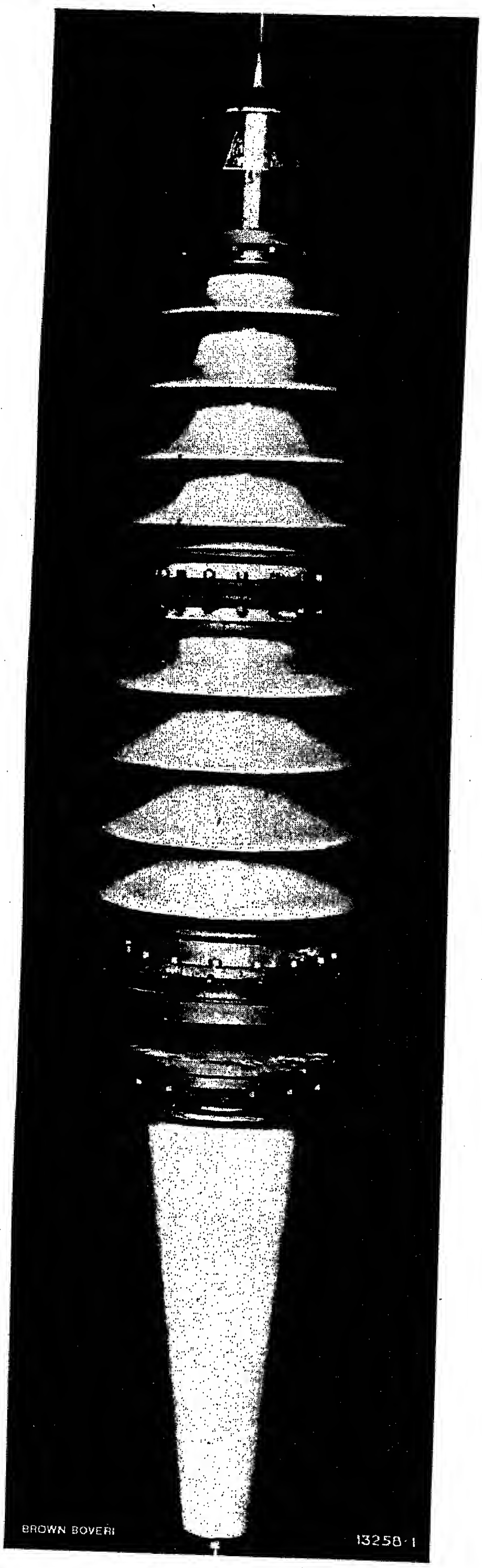


Fig. 38. — Oil-filled bushing for 150'000 V.
Breakdown pressure in rain 300'000 V.

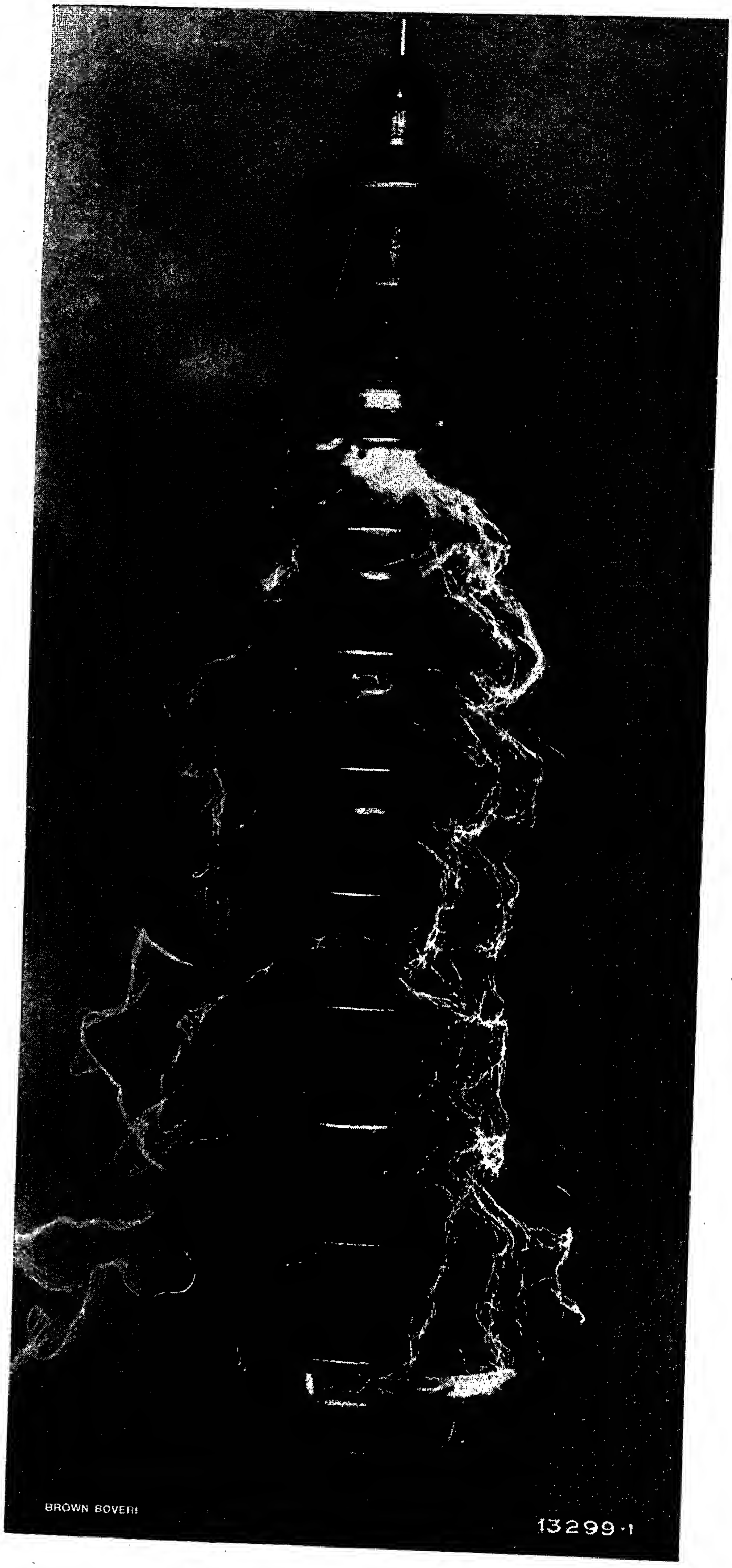


Fig. 39. — Oil-filled bushing flashing over at 280'000 V, with rain falling at the rate of 2·5 mm per minute.

The explosion gives rise to a certain increase of pressure in the cell containing the apparatus. As a rule, it is not possible to make the walls of the cell strong enough to withstand this pressure for a fairly long time, and it is consequently necessary to provide some arrangement for allowing immediate expansion. The iron expansion valves generally used for this purpose in the earlier days are insufficient, on account of their relatively large inertia. Brown, Boveri & Co. have therefore departed from the practice of fitting cells with such valves. They consider the best solution is to have the switch cells built at one of the outer walls of the building, and to provide in this wall large windows or weak sections of eternit at each cell. When an explosion occurs, these give way at once, and consequently a large opening to the outside atmosphere is provided.

The use of cells can be avoided altogether if the circuit breakers are made explosion-proof, and mounted in sheds as described hereafter under section *(c)*. This arrangement requires somewhat more space, since explosion-proof breakers are made practically only with cylindrical tanks and of the single-phase type.

(b) In the open air.

Only in the case of extra-high tensions is it as a rule economical to instal the circuit breakers in the open air. Against the reduction in the cost of the installation must be set the increased difficulty of attendance, and the fact that the apparatus is not protected from the weather.

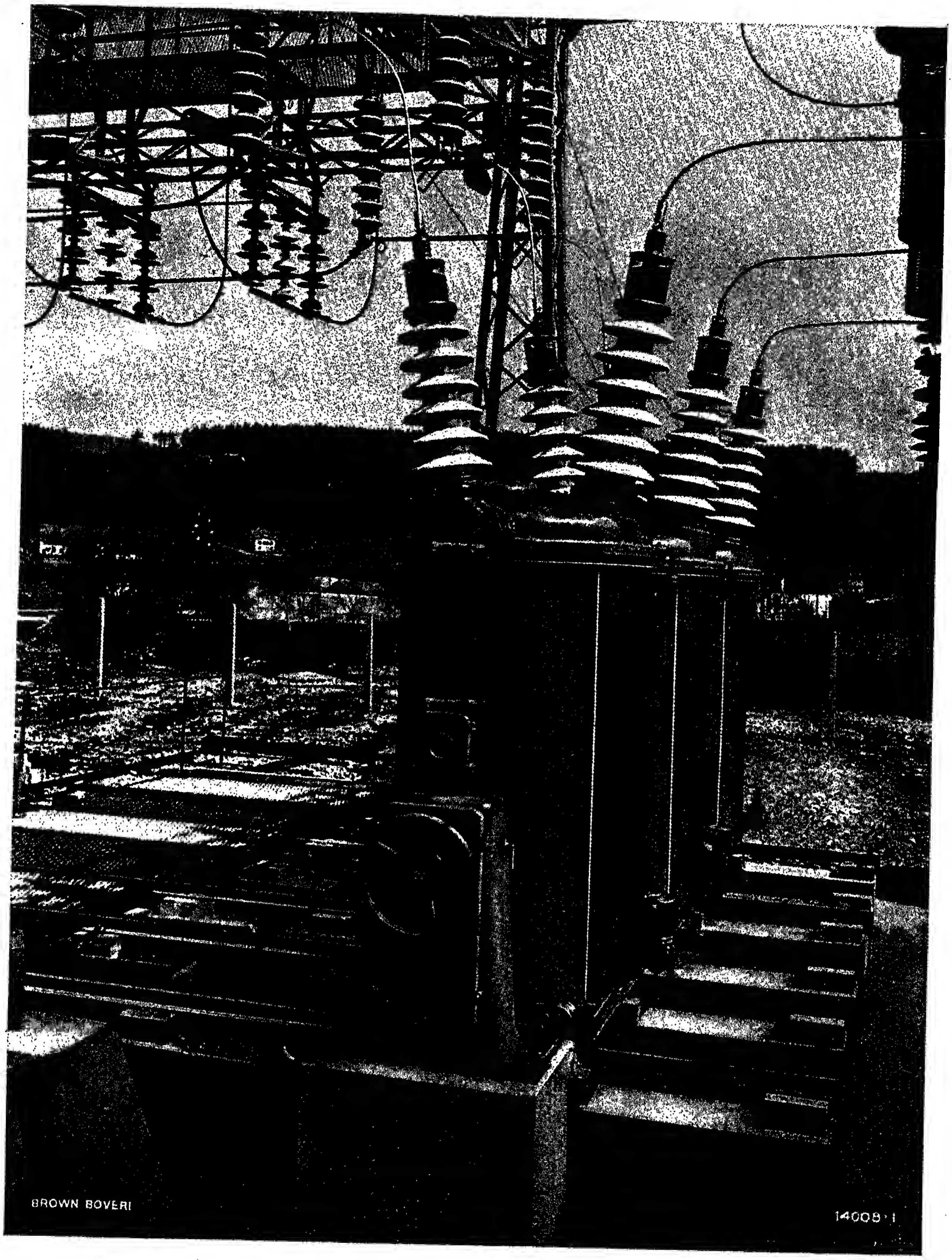


Fig. 40. — Set of three single-pole oil circuit breakers for 110'000 V in the Gœsgen outdoor substation, Swiss Power Transmission Co.

The circuit breakers, as well as the operating gear, auxiliary apparatus, and connections of outdoor installations, must be such that they are not affected by the weather. The bushings of the breaker terminals, in particular, must be of sufficient size to prevent flashovers from taking place when it rains. For this reason, oil-filled bushings (Fig. 38) have been adopted. A 110-kV Brown Boveri oil circuit breaker for outdoor use is shown in Figs. 8 and 9, a 150-kV breaker of similar type in Figs. 14 and 16, and the inside of the operating pillar is seen in Fig. 15. Fig. 40 shows a group of three oil circuit breakers for 110 kV in the outdoor station at Gœsgen of the Swiss Power Transmission Co. (Schweizerische Kraftübertragungs-A.-G.).

As the circuit breakers in outdoor plants are subjected directly to the frost in winter, it may be necessary to provide special electric heating apparatus to prevent the oil from setting.

(c) In open sheds.

To avoid the principal drawbacks of open-air stations without going to the expense of providing regular switch rooms, Brown, Boveri & Co. have suggested placing the circuit breakers in sheds. The tanks of the apparatus are buried in the ground, the lids made explosion-proof, and vents provided for leading off any gases that may be generated. No partitions or walls of any kind are required, so that supervision is easy, while the use of expensive leading-through insulators, such as are necessary in switch houses for high-tension current, is avoided.[1]

[1] See Elektrotechnische Zeitschrift, 1922, p. 1142.

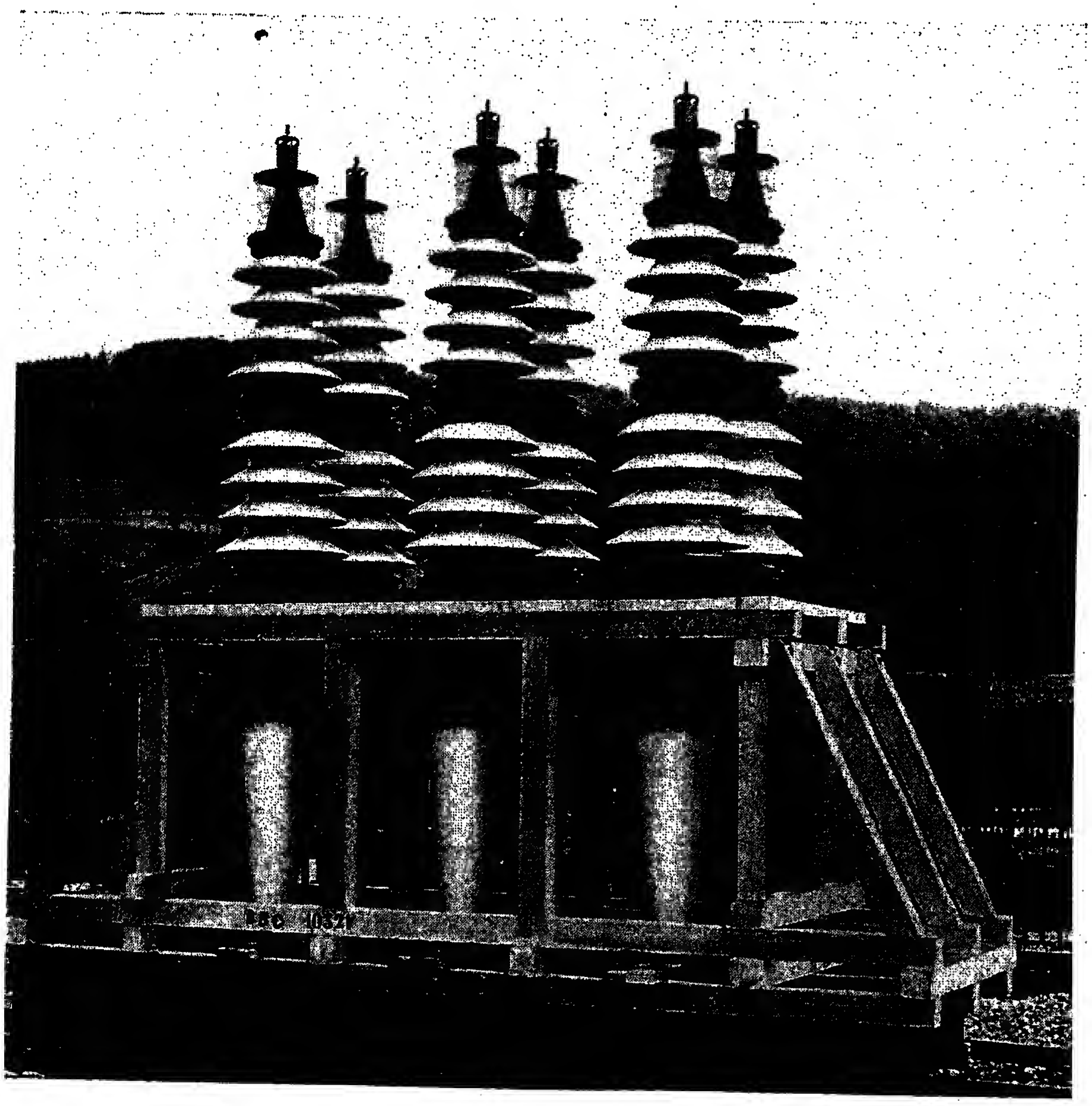


Fig. 41. — Porcelain bushings for 15'000-V, single-pole, outdoor-type oil circuit breakers, ready for dispatch.

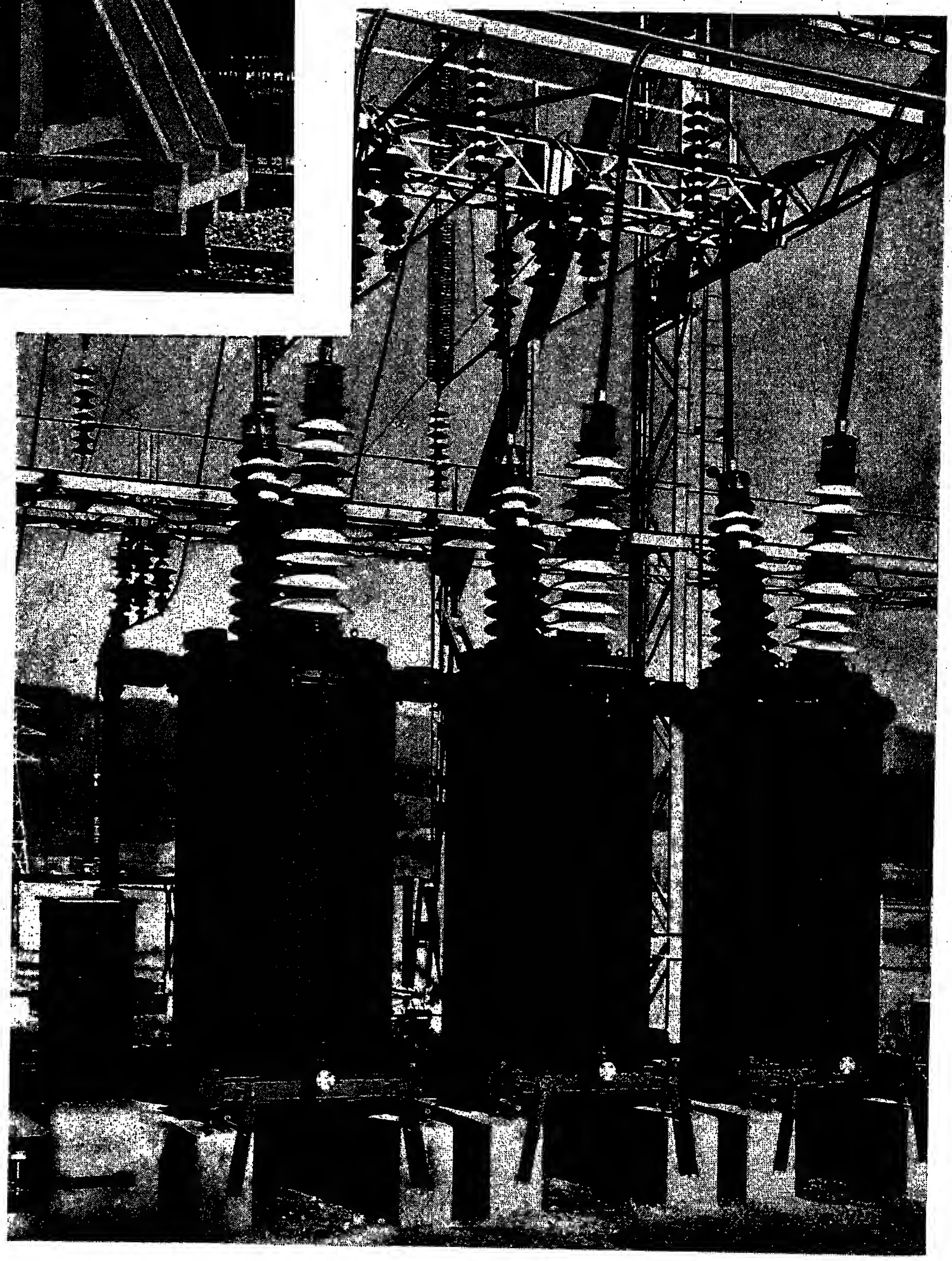


Fig. 42. — Set of three single-pole oil circuit breakers for 150'000 V in Bassecourt outdoor substation, Bernese Power Works, Berne.

10. SUMMARY OF THE PRINCIPLES ON WHICH THE DESIGN OF BROWN BOVERI OIL CIRCUIT BREAKERS IS BASED.

The most important principles for the design of Brown Boveri circuit breakers, as based on the result of wide experience and numerous tests, are briefly the following:—

(a) The use of more or less numerous breaking points according to the tension.

(b) Welding the tank in such a way that it has the maximum strength to resist internal pressures.

(c) Insulating lining for the tank and insulating partitions between the different contacts.

(d) Employment of contact springs with a large initial compression.

(e) No other insulating material than oil between the contacts of the same pole when the breaker is open.

(f) Ample depth of oil above the contacts.

(g) Possibility of fitting resistances for breaker protection — this is especially recommendable when very heavy currents have to be interrupted.

(h) Possibility of fitting resistances for transformer protection without diminishing the rupturing capacity of the breaker — this should be done whenever switching operations are undertaken on large transformers at no load.

(i) Protective resistances for transmission lines that are switched in and out unloaded can probably be dispensed with in all cases by employing circuit breakers with several breaking points.

G. Bruhlmann. (J.F.L.)

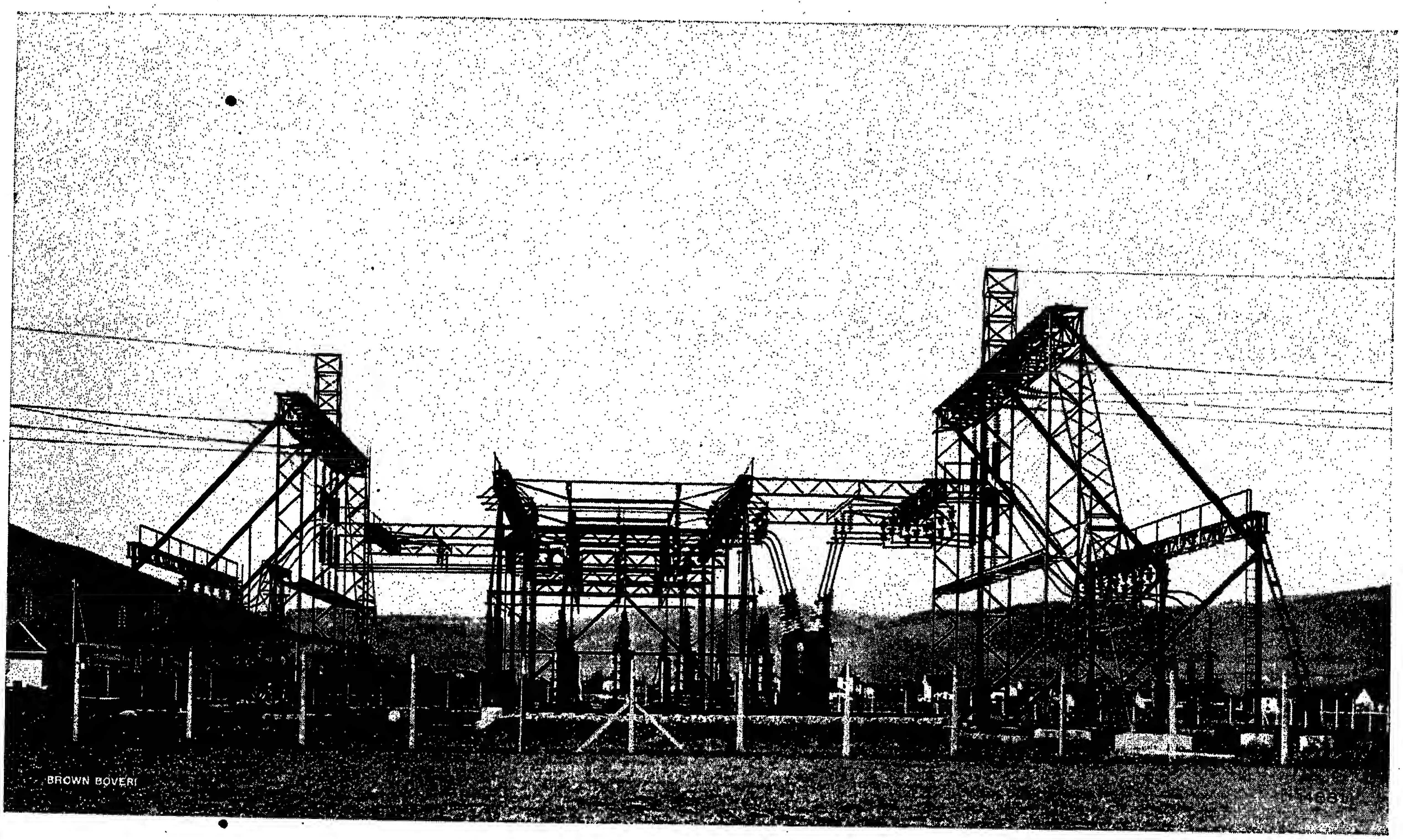


Fig. 43. — General view of Bassecourt outdoor substation, Bernese Power Works, Berne.

VOL. X APRIL, 1923 No. 4

THE BROWN BOVERI REVIEW

EDITED BY BROWN, BOVERI & CO., BADEN (SWITZERLAND)

LUCERNE, THE STARTING POINT OF THE ELECTRIFIED ST. GOTHARD SECTION OF THE SWISS FEDERAL RAILWAYS.

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THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & CO., BADEN (SWITZERLAND)

VOL. X APRIL, 1923 No. 4

The Brown Boveri Review is issued monthly. Single numbers: 1.20 francs (1 shilling). Yearly subscription: 12 francs (10 shillings).

OIL CIRCUIT BREAKERS OF LARGE RUPTURING CAPACITY.[1]

Decimal index 621. 317. 35.

8. TESTS WITH LARGE SHORT-CIRCUIT LOADS.

(a) Tests in Lœntsch power station.

SOME years ago, a series of tests was made in the Lœntsch station with a set of three single-pole oil circuit breakers, Type OE 30/400, for 27'000 V, 100 A. The design of this apparatus is no longer modern — in size it corresponds roughly to the present type A 12/1 for 35 kV. The alternator available for the tests had an output of 5250 kVA, 8000 V, 375 r.p.m., and was connected to a transformer for 8000/27'000 V. With the short circuits, the breaker was tripped by its own overload time-limit relay, which was set for minimum time lag. The apparatus was provided with a resistance for breaker protection, but the ohmic value of it was not the most suitable. The switching stages before and after the resistance had each two breaking points.

When the current was interrupted on a short circuit with a transformer tension of 31'500 V and about 600 to 900 A, the arc was found to be about 70 mm long, while there was not much smoke produced or oil thrown out. This short-circuit load represents about 32'000 to 50'000 kVA, three phase.

(b) Tests in Biaschina power station, Bodio.[2]

The tests in this station were made on a larger scale. The electrical data were recorded each time by two oscillographs, and the behaviour of the breaker was carefully observed.

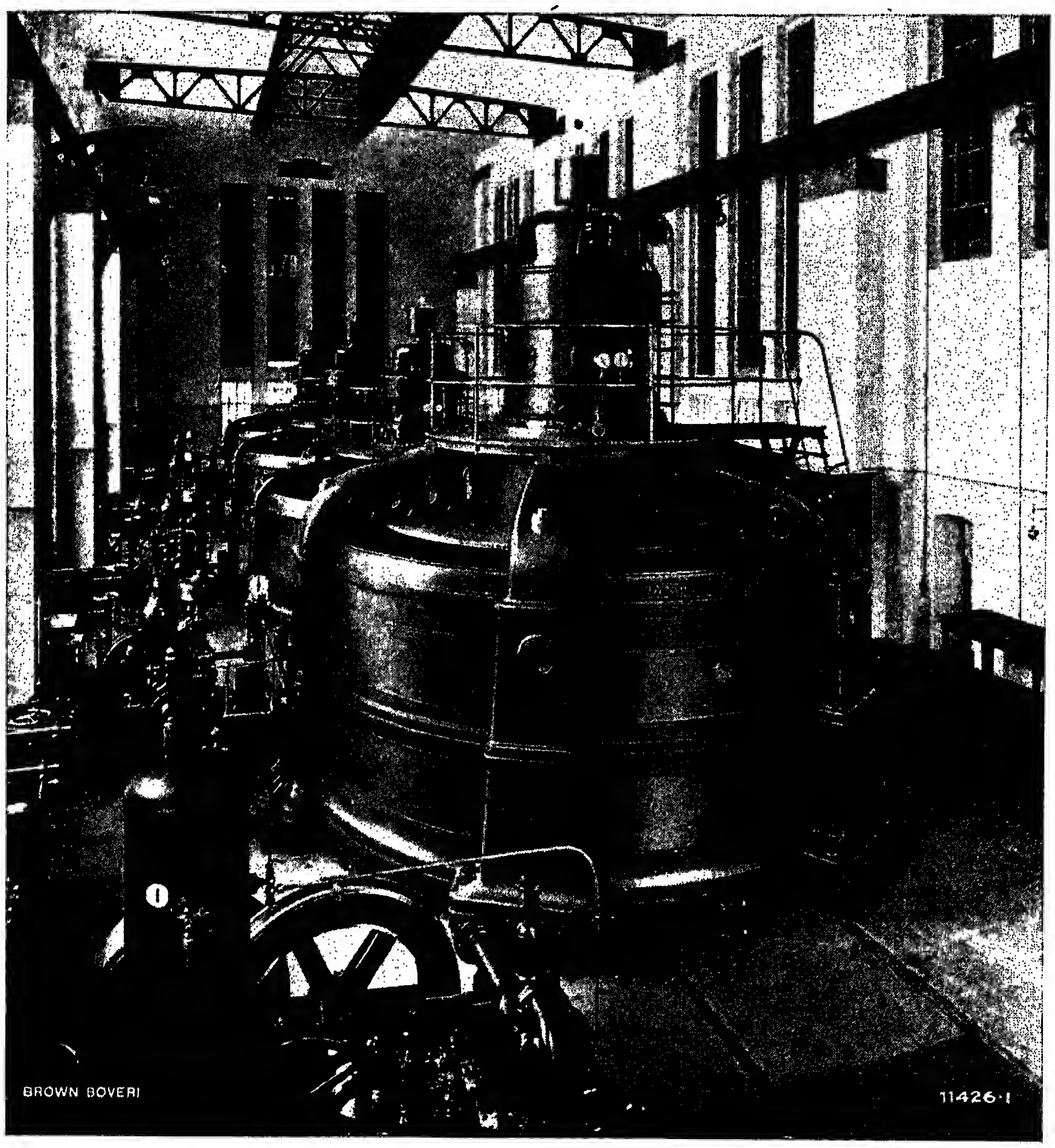

Fig. 17. — Machine room of Biaschina power station, Bodio (Switzerland). Three alternators of 8800 kVA each, one alternator of 14'600 kVA, 8000 V.

The plant consisted of two alternators of 8800 kVA each, and one of 14'600 kVA, 50 cycles, so that the total power available was 32'200 kVA. The interior of this power station is shown in Fig. 17. For the tests, all three machines were run in parallel, or else only one used alone, and, in order to have the highest possible load on the switch, the current was always interrupted with the short-circuit peak load, and not on a sustained short circuit. To ensure this, the breaker was not

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[1] Concluded from March, 1923.

[2] This plant was kindly placed at the disposal of Brown, Boveri & Co. by the Société Anonyme Motor for making short-circuit tests.

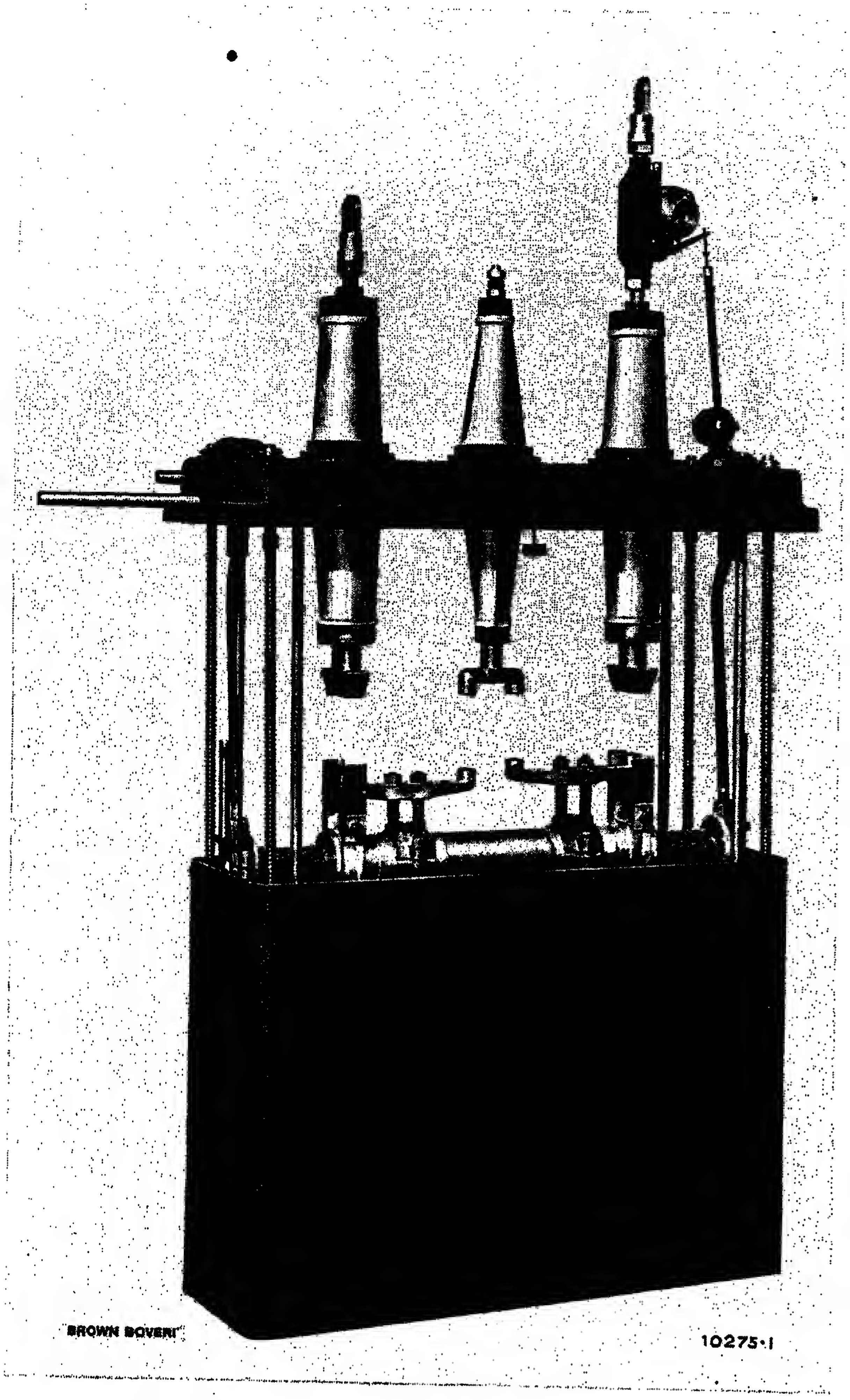


Fig. 18. — Single-pole oil circuit breaker type D 12/1c, 35'000 V, 1000 A, with third bushing and built-on series time-limit relay.

tripped by an overload relay, whose operation would have had a certain time lag, but directly by means of the switch which was used to cause the short circuit. This enabled loads to be interrupted that corresponded to sustained short-circuit loads of a plant having three times the output. That is to say, when the three alternators were working in parallel, the circuit breaker dealt with a load of about the same value as would have to be interrupted under regular working conditions in a station of 100'000 kVA when a short circuit took place.

The three circuit breakers employed for the tests were of the type D 12/1, and had each three bushings for 35'000 V. One of these breakers is shown in Fig. 18 with the tank lowered. There were normally four breaking points in each apparatus, and trials were made without protective resistances as well as with such accessories of different ohmic values. It was also possible to modify the circuit breakers in such a way that each one had 14 breaking points.

The comparative tests with different numbers of breaking points were carried out with one alternator at a reduced pressure of about 6000 V. The results obtained are given in the following table, which contains the average values of all the tests made.

Influence of the number of breaking points when rupturing the sudden short-circuit current of an alternator of 8800 kVA, 6000 V.

	No. of breaking points 4	14
Duration of arc in half periods (50 cycles per second) . . .	6·9	3·25
Arcing energy in kWsec . . .	57	44
Approx. max. pressure impulses in the oil . . . . . . kg/cm²	3·9	5·9
Noise produced	loud	moderate to weak
Production of smoke noticeable .	considerable	small
Speed of breaking at contact bar . . . . m/sec	0·94	0·72
Speed of breaking $\times$ number of breaking points	3·75	11·0

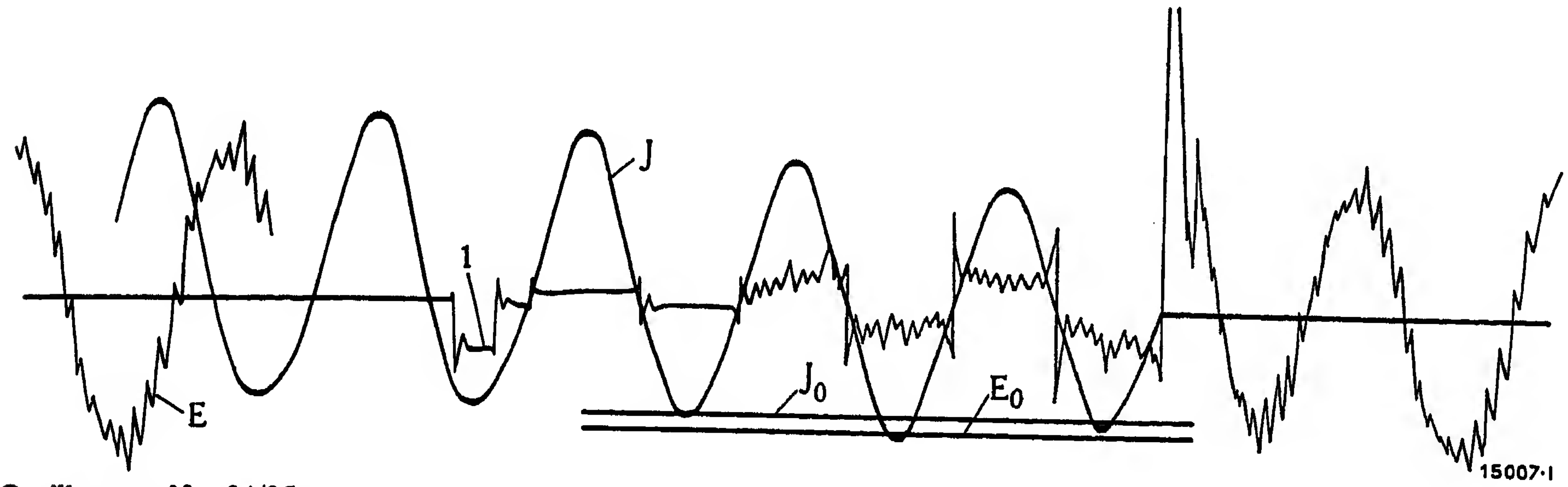
The oscillograms 84/25a and b (Figs. 19 and 20) were made during one of the tests with each number of breaking points, the two oscillographs being coupled so that they worked in synchronism. The oscillograms (a) give the current and pressure at one pole of the circuit breaker being tested, while those marked (b) refer to the pressure impulses and the potential to earth in the same phase. The tension at the breaker is disturbed from the moment the arc is extinguished. This arises from the fact that the potential transformer used for measuring purposes then forms an oscillatory system in conjunction with the capacity of the line switched out.

The instant the rupturing process begins is indicated by a mark on the curve giving the potential at the breaker.

The arcing energy was mesured with the assistance of a ballistic wattmeter specially constructed for these tests. When the current and pressure coils of this instrument are connected to the switch through suitable measuring transformers, its needle moves at the moment of breaking by an amount representing the integral

$$\int e\,i\,dt$$

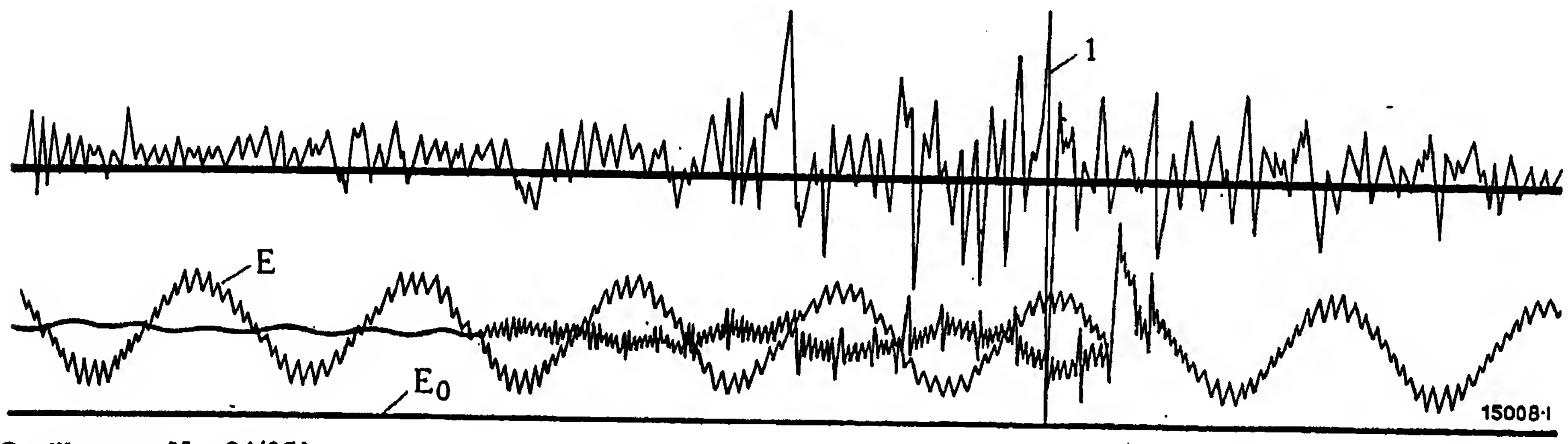
which is, therefore, proportional to the arcing energy.



Oscillogram No. 84/25 a.

Fig. 19. — Rupturing process when a circuit breaker with four breaking points is tripped during a short circuit; pressure 5800 V, alternator output 8800 kVA.

J. Short-circuit current.
E. Potential at breaker in one phase.
J_0. Calibrating current, $J_0 = 2450$ A.
E_0. Calibrating pressure, $E_0 = 5900$ V.
1. Moment the contacts open.



Oscillogram No. 84/25 b.

Fig. 20. — Rupturing process when a circuit breaker with four breaking points is tripped during a short circuit; pressure 5800 V, alternator output 8800 kVA.

E. Potential of a phase to earth.
E_0. Calibrating pressure, $E_0 = 6250$ V.
1. Pressure impulses in the oil. (Approximate scale: 1 mm = 0·2 kg per cm².)

The pressure impulses in the oil were noted near the side of the tank by means of a special measuring apparatus which caused currents proportional to the oil pressure to flow, these currents being recorded by the oscillograph. This device did not operate entirely satisfactorily, so that the figures can only by taken as giving a rough idea of the magnitude of the impulses.

Attempts were also made to measure the volume of gas produced. For this purpose, a hood of suitable proportions made of bituba plates was placed in the oil just over the contacts of the breaker under observation. As the hood did not remain tight, due to the pressure waves in the oil, the data obtained are unfortunately not reliable.

The results of the tests may be summed up as follows:—

The observations made on the circuit breaker at Bodio showed quite a distinct improvement in the rupturing process when there was a large number of breaking points. The figures obtained in this respect were, however, not so favourable as had been anticipated: with $3^1/_2$ times as many breaking points, the duration of the arc was reduced by half, while the aggregate length of the different portions of the arc was increased by a quarter. These results correspond roughly to the conditions found during the tests with 700 kVA (see Fig. 7). They do not justify the construction of switches with such a large number of breaking points, especially as the arcing energy is only very slightly reduced, while the pressure impulses are more pronounced. This can be readily understood since the magnitude of the impulses is practically independent of the duration and length of the arc, whereas, with many breaking points, there are several arcs to cause pressure rises in the oil simultaneously.

The more or less favourable effect of the multiple breaks is undoubtedly dependent on the tension of the system to which the circuit breaker is connected, their adoption being all the more advantageous the higher the pressure is. The results of the above series of tests lead to the conclusion that even with only 6000 V, the rupturing process is improved by the use of multiple breaks, and that with much higher pressures, the effect may be expected to be correspondingly greater.

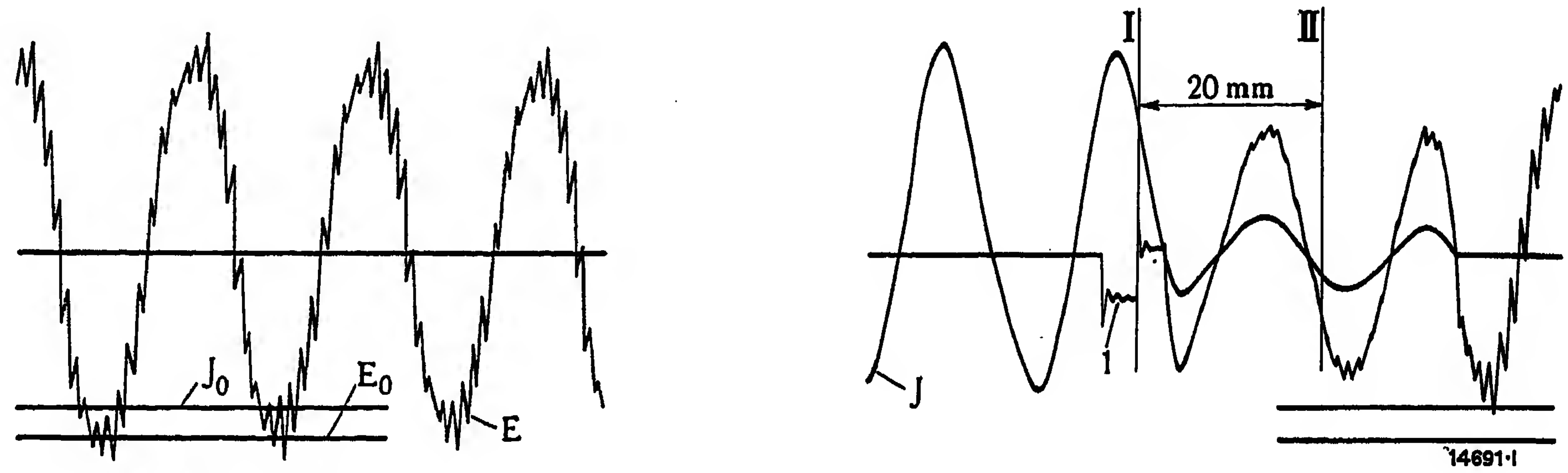
The results of the investigations made by Dr. Marguerre at Ryukanfos[1] agree with those obtained from the tests described above. Of the five circuit breakers of various makes which he employed, that furnished by Brown, Boveri & Co. had the largest number of breaking points, and was the only one that stood up to the duty required.

Even in earlier days, Brown, Boveri & Co. built with success oil circuit breakers having multiple contacts. Among these may be specially mentioned a large number of breakers, of a type now superseded, with 10 breaking points and only 5 cm closing distance which have been in use nearly 12 years in a steam-turbine-driven central station, of more than

[1] Elektrotechnische Zeitschrift, 1912, p. 709.

100′000 kVA capacity at 6000 V, in Buenos-Aires. With these circuit breakers, there has never been the least trouble.

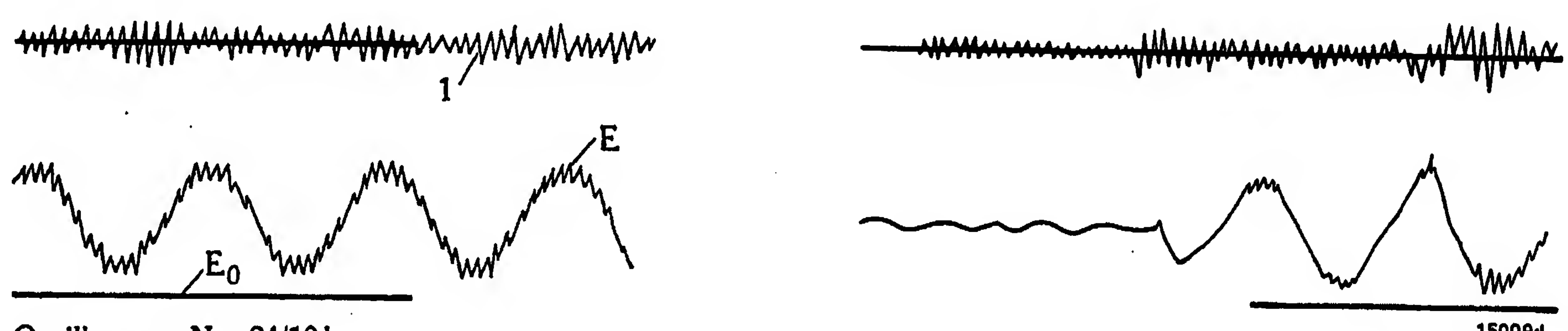
The tests to determine the effect the use of resistances for protecting the breaker has on its rupturing capacity were also made with a pressure of 6000 V and short circuits with one alternator. Three different sizes of resistances were employed, whose ohmic values were equal to 1, 4, and 8 times the short-circuit impedance of the alternator. The apparatus had two breaking points in each switching stage.



Oscillogram No. 84/19a.

Fig. 21. — Rupturing process when a circuit breaker with two stages, each having two breaking points and a protective resistance of four times the short-circuit impedance is tripped during a short circuit; pressure 5800 V, alternator output 8800 kVA.

J. Short-circuit current.
E. Potential at breaker in one phase.
J_0. Calibrating current, $J_0 = 2670$ A.
E_0. Calibrating pressure, $E_0 = 7300$ V.
1. Moment the contacts open.
I, II. Moment the first or second stage opens.



Oscillogram No. 84/19b.

Fig. 22. — Rupturing process when a circuit breaker with two stages, each having two breaking points, and a protective resistance of four times the short-circuit impedance is opened during a short-circuit; pressure 5800 V, alternator output 8800 kVA.

E. Potential of a phase to earth.
E_0. Calibrating pressure, $E_0 = 7150$ V.
1. Pressure impulses in the oil. (Approximate scale: 1 mm = 0·1 kg per cm².)

The oscillograms 84/19a and b (Figs. 21 and 22) show the rupturing conditions when using a resistance corresponding to four times the impedance. The arc at stage I lasted 0·4, and that at stage II, 1·8 half periods.

The average values of the results obtained are given in the following table, which also contains those got from the same circuit breaker when employed with four breaking points and no resistance.

Effect of a resistance for breaker protection when rupturing the instantaneous short-circuit current of an alternator of 8800 kVA, 6000 V.

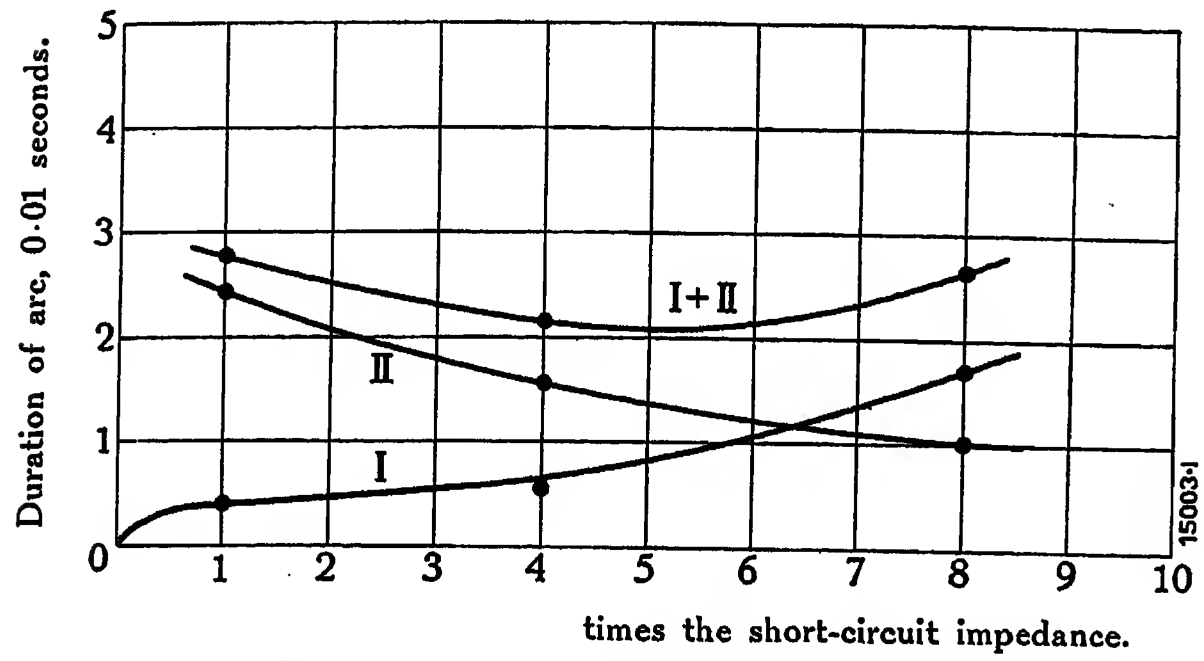
	Resistance			
	none	1	4	8
	times the short circuit impedance of the alternator			
Duration of arc in half-periods (50 cycles), stages I and II . . Sum I and II . . .	6·9	0·33+2·4 =2·73	0·6 +1·5 =2·1	1·65+1·0 =2·65
Arcing energy for the two stages in kW sec	57	50	25	5·5
Max. pressure impulse in the oil in kg/cm² . .	3·9	0·65	0·27	0·25
Approx. volume of gas in cm³	150	35	32	37
Noise produced . . .	loud	←—— very weak ——→		

When comparing the different length of time the arc lasted, it must be remembered that without resistances there were arcs at four contacts, whereas with resistances, arcs are struck at only two contacts. The total duration of the arc must be divided by two in order to obtain the average time for each stage. The arcing energy at the two stages was determined as follows:— The energy absorbed by the resistance was calculated, and subtracted from the reading of the ballistic wattmeter, which corresponded to the total energy in the resistance and breaker together. The measurement of the quantity of gas generated was reliable when using a resistance, as the collecting hood was not affected by the very light impulses produced in the oil.

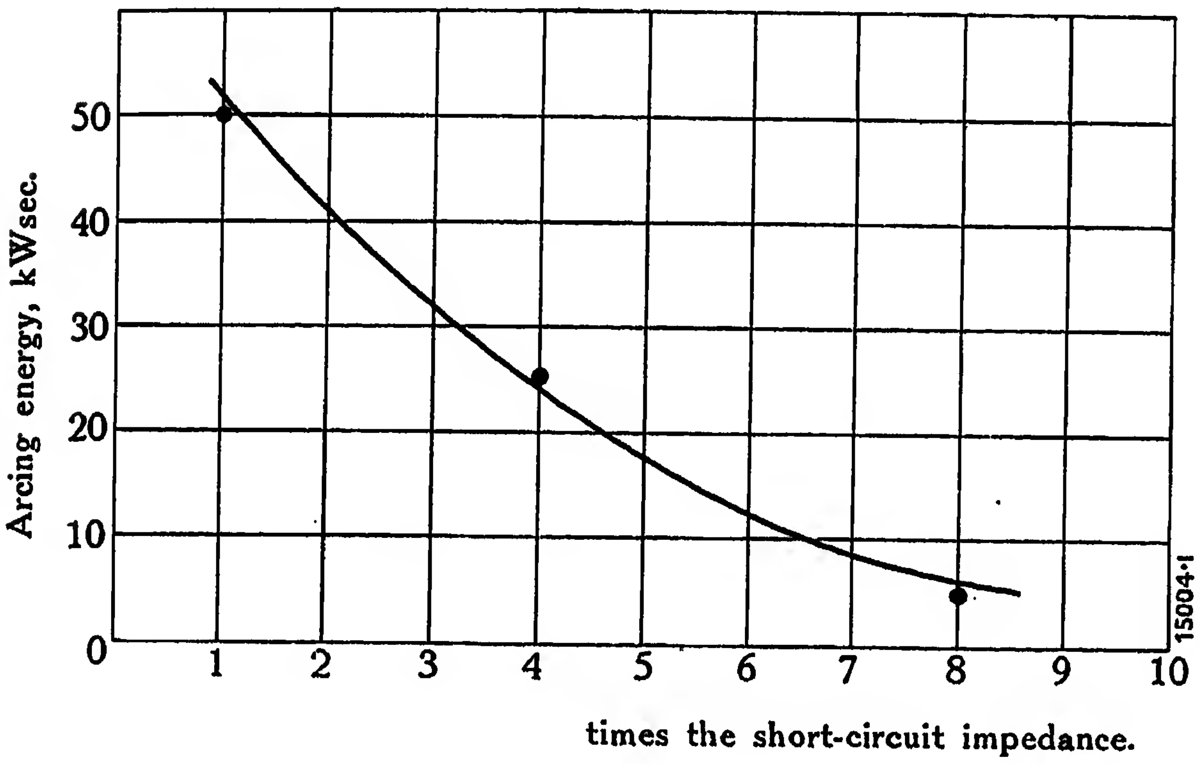
Curves showing the duration of the arc, the arcing energy and the value of the pressure impulses are given in Figs. 23, 24 and 25.

Conclusions. From these curves, it can be seen that neither the pressure impulses nor the arcing energy, which is the most important factor, reach their minimum value with the largest resistance used during the tests. It would appear that a resistance equal to about *10 times the short-circuit impedance is the most favourable amount,* but that this figure need not be rigidly adhered to.

The results also give an idea of the increase possible in the rupturing capacity by providing a



I. Stage I. II. Stage II. I + II · Sum of I and II.



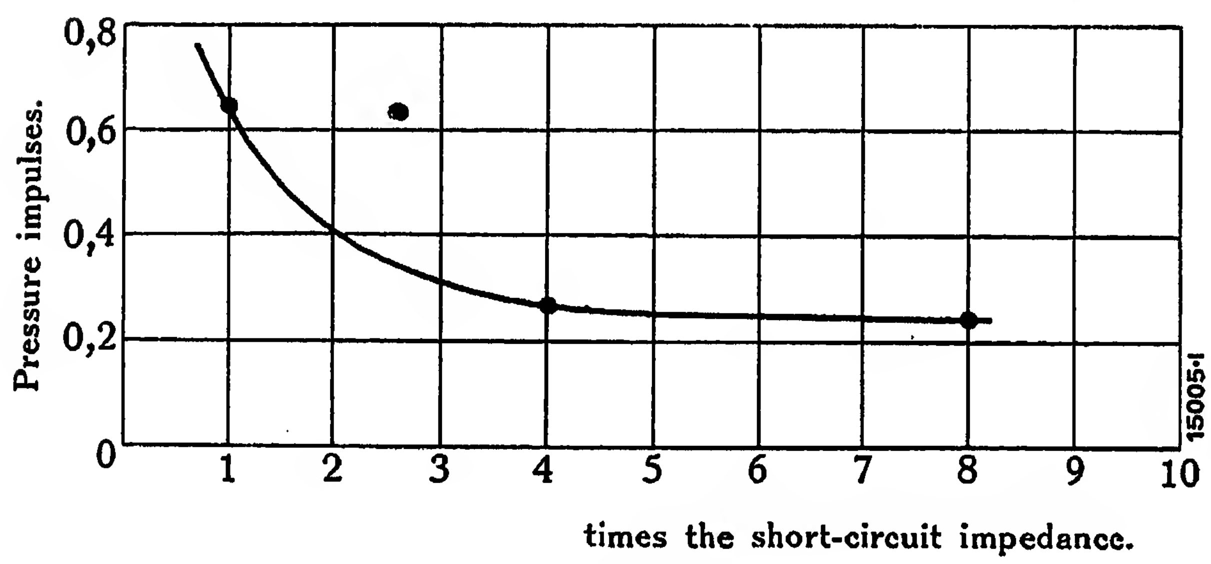


Fig. 23, 24, 25.

Duration of arc, arcing energy and pressure impulse when rupturing a three-phase short-circuit load of about 26'000 kVA at 6000 V.

resistance for the circuit breaker. As compared with an apparatus without such a resistance, the improvement can be taken to be roughly as follows:— The duration of the arc falls to $^1/_4$, the arcing energy to $^1/_{10}$, the pressure impulses to $^1/_{15}$, and the volume of gas to $^1/_5$ when a resistance is employed. It can therefore be assumed with sufficient margin, that *a circuit breaker with a resistance has four times the breaking capacity* of the same apparatus without it.

Tests with the alternator of 14'600 kVA, at about 8000 V (with full excitation) gave the following average results with multiple breaks and no resistance:

Duration of arc in half periods (50 cycles)	5·5
Arcing energy in kWsec	130
Approx. max. pressure impulse kg/cm² . .	4·3

The conditions during one of these tests can be seen from the oscillograms 84/35 a and b in Figs. 26 and 27. There was a fair amount of oil thrown out, and quite a large quantity of gas produced. Judging from experience, however, it seemed that the full breaking capacity of the apparatus had not nearly been reached. This is confirmed by the length of the arc, which measured only about 4 cm, whereas a length of about 10 cm is allowable with the breaker in question.

The oscillograms 84/37 a and b (Figs. 28 and 29) show what took place when the momentary short-circuit current of all three alternators running in parallel was interrupted. The tension at the very end of the rupturing process is not given in these diagrams. From the data obtained, it can be concluded that the length of the arc was in the neighbourhood of 6 cm, i. e., still considerably below the maximum length of 10 cm allowable. The figure for the pressure impulses in the oil was only about 3·5 kg per cm². From all the tests made, it did not appear to rise with increasing loads.

In all, about 40 sudden short circuits were made with the various machines, which were not harmed in the slightest by the strenuous requirements they were called upon to meet.

(c) Tests with a 12'000-kVA turbo-alternator.

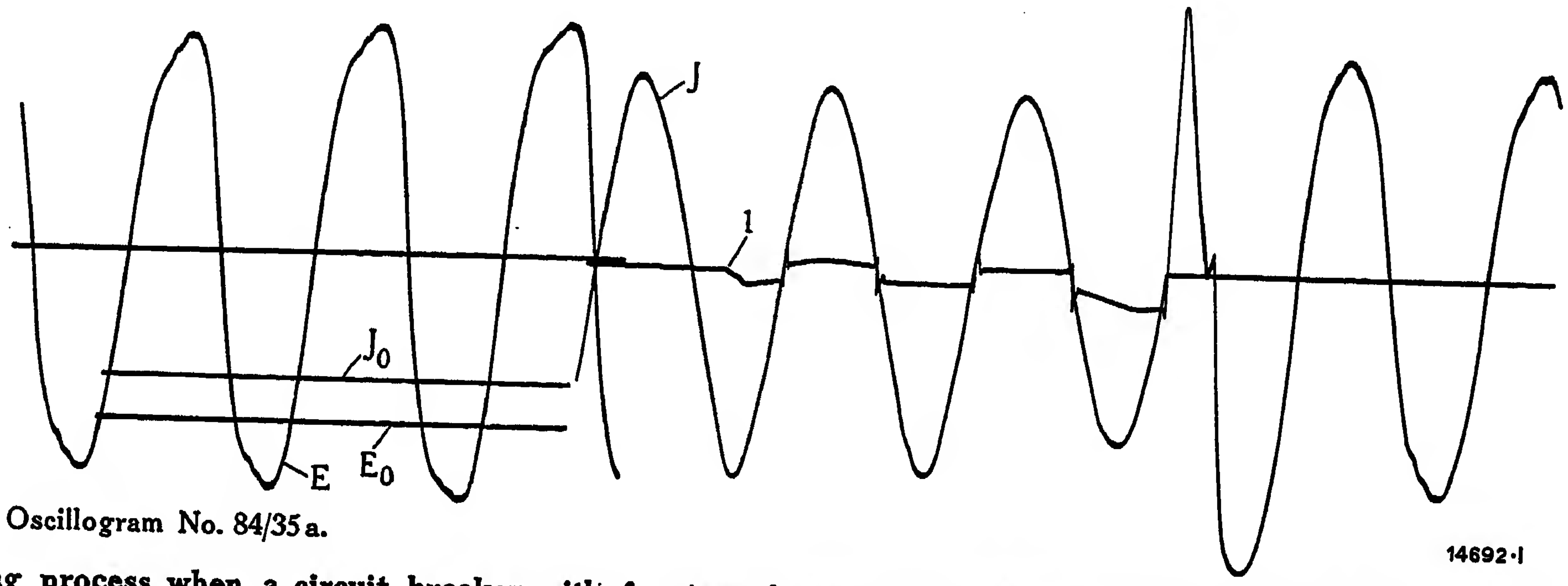
This machine is shown in Fig. 30 as erected in the turbine testing department of Brown, Boveri & Co. for making short-circuit tests. Its speed is 3000 r. p. m., the tension 11'000 V, and the frequency 50 cycles. As the foundation was not considered substantial enough, the set was specially clamped down to withstand the sudden stresses accompanying the short circuits. The piping visible in the illustration was provided for the purpose of admitting steam to the alternator in the event of a fire starting there.

Three different types of oil circuit breakers were tested, namely:—

I. A single-pole breaker for 35'000 V, 600 A with six breaks, but no protective resistance.

II. A standard triple-pole breaker, Type A 8/3, for 12'000 V, 200 A, as shown in Fig. 1.

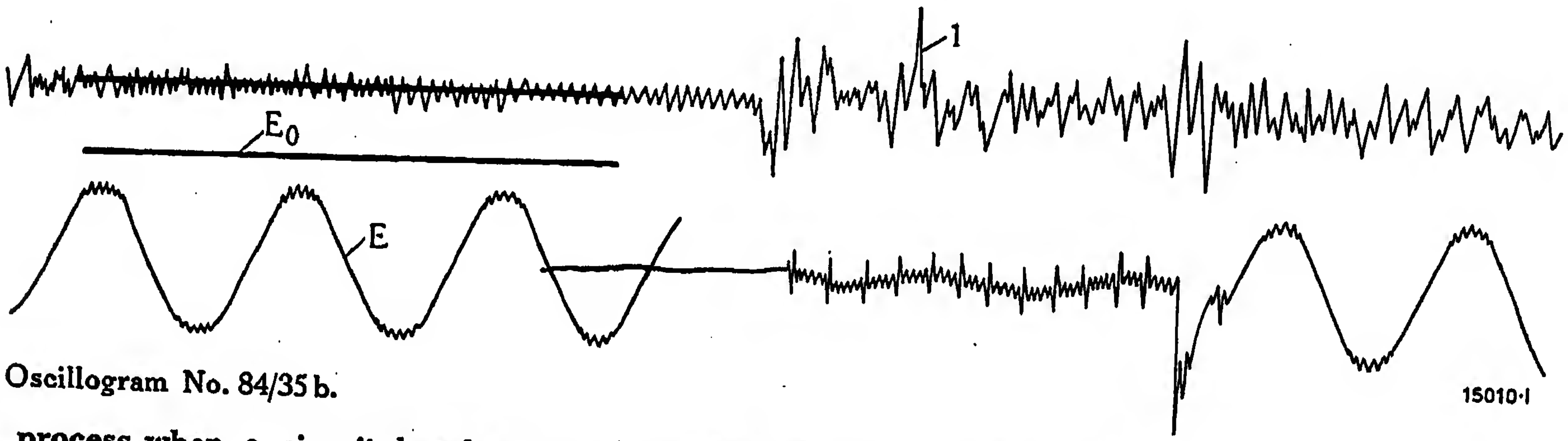
III. Three single-pole breakers, as used on the Gothard locomotives, for 15'000 V, 350 A, with a resistance for transformer protection (Figs. 33 and 34).



Oscillogram No. 84/35 a.

Fig. 26. — Rupturing process when a circuit breaker with fourteen breaking points is tripped during a short circuit; pressure 8100 V, alternator output 14'600 kVA.

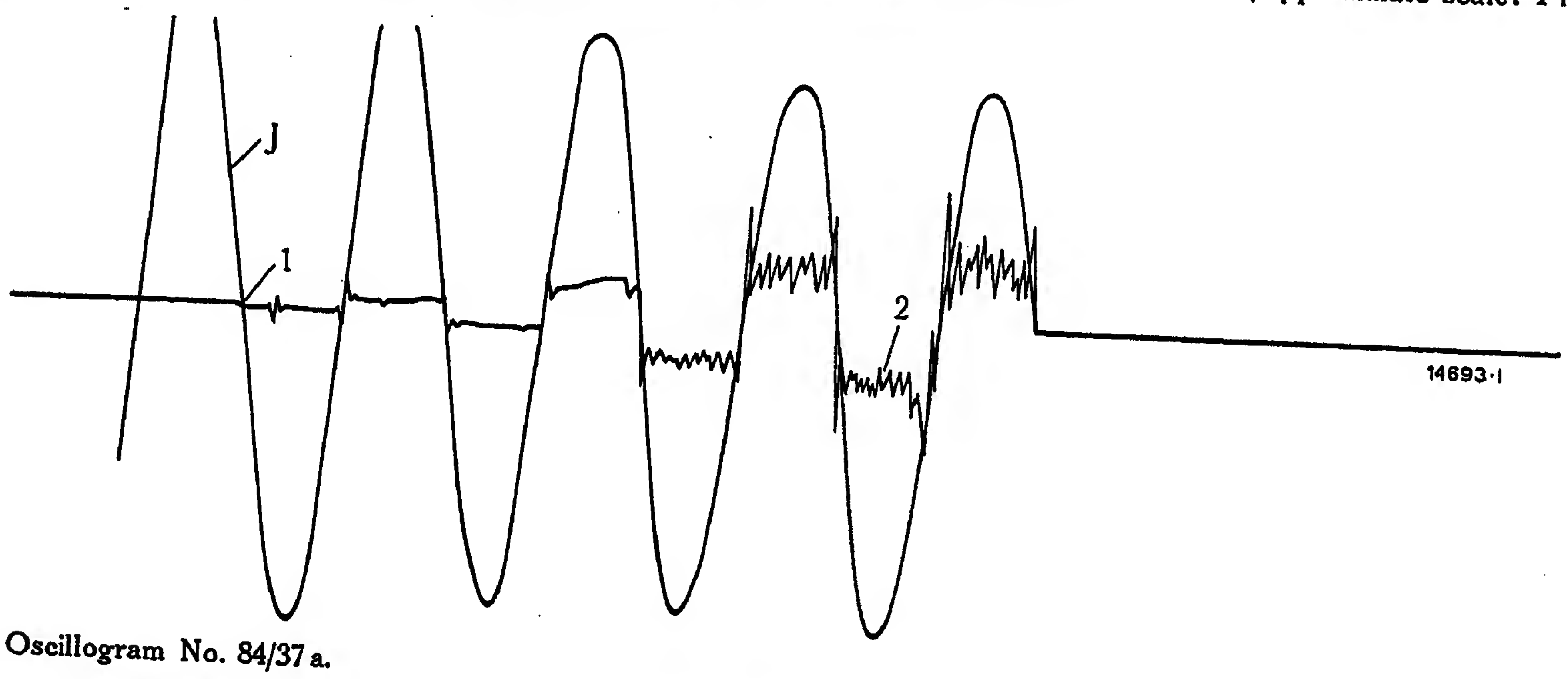
J. Short-circuit current.
E. Potential at breaker in one phase.
J_0. Calibrating current, $J_0 = 4930$ A.
E_0. Calibrating pressure, $E_0 = 6650$ V.
1. Commencement of the arc.



Oscillogram No. 84/35 b.

Fig. 27. — Rupturing process when a circuit breaker with fourteen breaking points is opened during a short circuit; pressure 8100 V, alternator output 14'600 kVA.

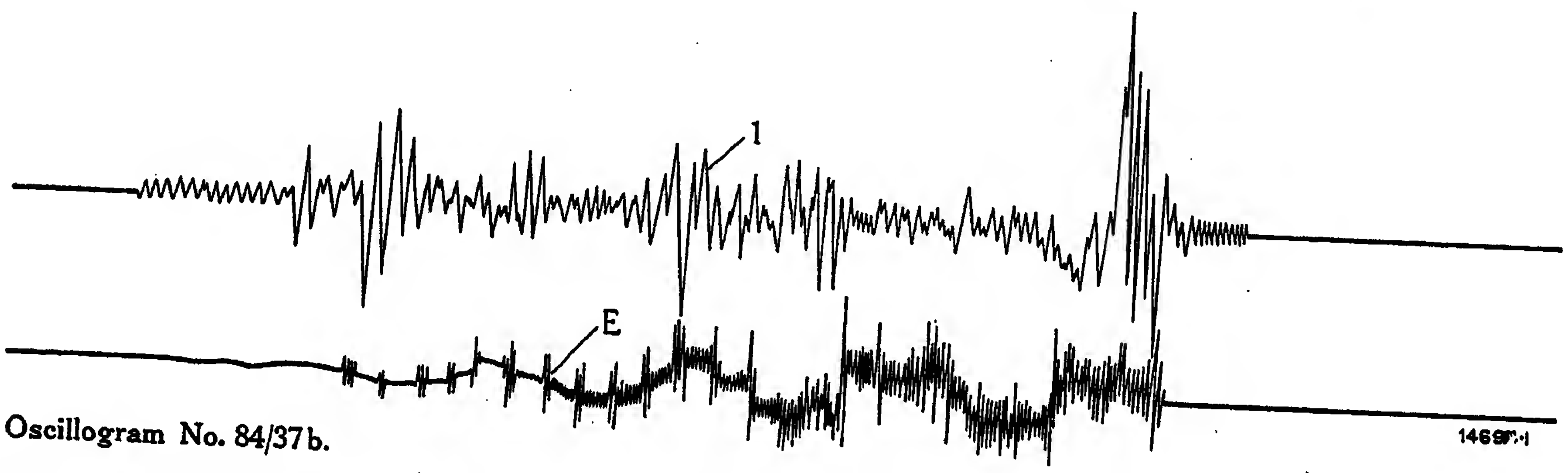
E. Potential of a phase to earth. E_0. Calibrating pressure, $E_0 = 9000$ V. 1. Pressure impulses in the oil. (Approximate scale: 1 mm = 0·5 kg per cm².)



Oscillogram No. 84/37 a.

Fig. 28. — Rupturing process when a circuit breaker with fourteen breaking points is opened during a short circuit; pressure 7750 V, aggregate output of the three alternators 32'200 kVA.

J. Short-circuit current. 1. Commencement of the arc. 2. Tension across the arc.



Oscillogram No. 84/37 b.

Fig. 29. — Rupturing process when a circuit breaker with fourteen breaking points is opened during a short circuit; pressure 7750 V, aggregate output of the three alternators 32'200 kVA.

E. Potential of a phase to earth. 1. Pressure impulses in the oil. (Approximate scale: 1 mm = 0·5 kg per cm².)

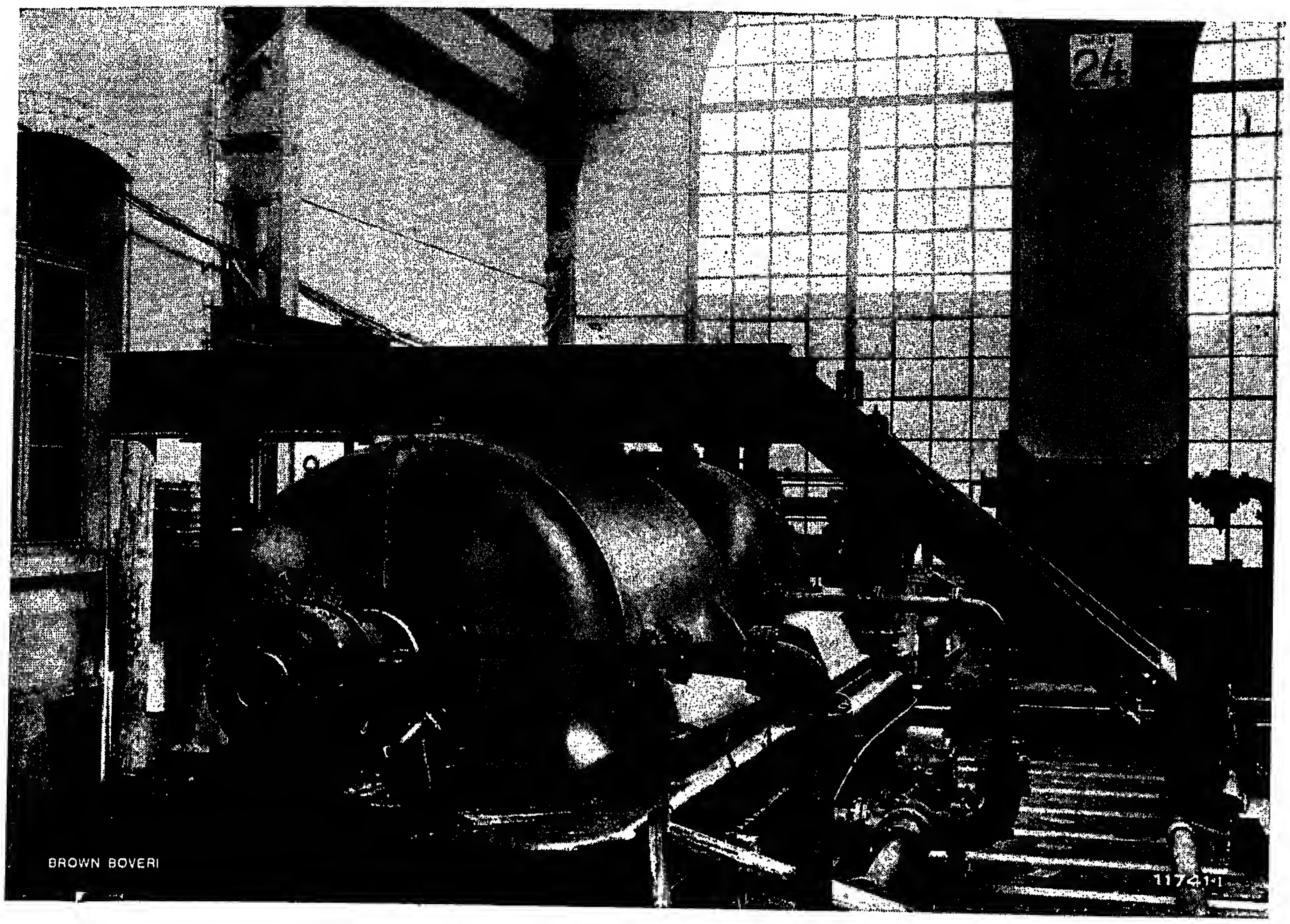


Fig. 30. — Turbo-alternator, 12'000 kVA, 11'000 V, 3000 r. p. m., as used for short-circuit tests in Baden works, Brown, Boveri & Co.

Tripping took place in all cases without time lag, so that the duty corresponded to the conditions met with in normal service in a generating plant having several times the output of that used for the tests in question.

I. Tests with a single-pole circuit breaker for 35'000 V. This apparatus was closed and tripped about 15 times. The oscillograms 111/7 and 111/9 (Figs. 31 and 32) refer to two of these tests. In the latter figure, which shows the conditions at closing and opening instantaneously with a pressure of 5300 V, the values of the current, etc. are as follows:—

Maximum peak current	22'500 A.
R. M. S. current while rupturing .	10'000 A.
Three-phase load while rupturing .	160'000 kVA.

Some of the tests were made with three-phase, and others with single-phase current. In a number of cases, the alternator was delta connected with a normal pressure of 6400 V, and this permitted very high short-circuit currents (up to 33'000 A peak value) to be reached. The duty required of the breaker was then heavier than with a lower current at a correspondingly higher tension.

The following tests were made on all three circuit breakers:—

1. The current was passed through the apparatus without it tripping.
2. The breaker was closed on a short circuit without tripping immediately after.
3. The short-circuit current was interrupted by the breaker.
4. The breaker was reclosed on the short circuit and allowed to trip again.

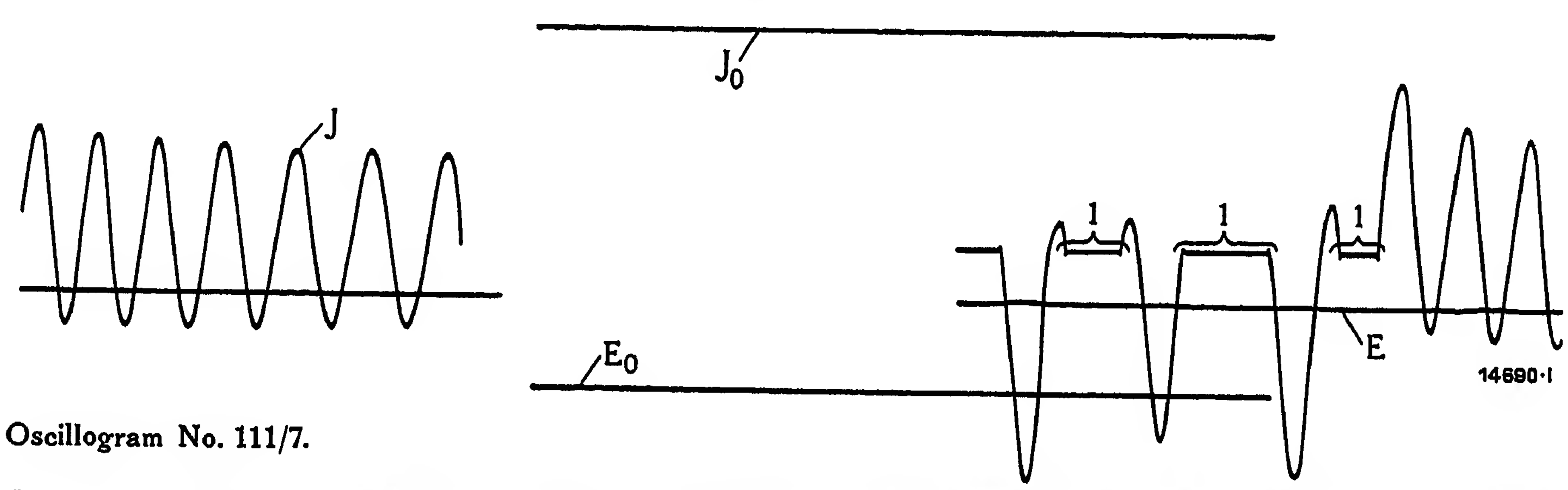


Fig. 31. — Closing on a short circuit by a 12'000 kVA turbo-alternator with a 35'000 V circuit breaker.

J. Short-circuit current.
E. Potential at breaker.
J_0. Calibrating current, $J_0 = 21'300$ A.
E_0. Calibrating pressure, $E_0 = 3040$ V.
1. Interruption of current due to contacts parting.

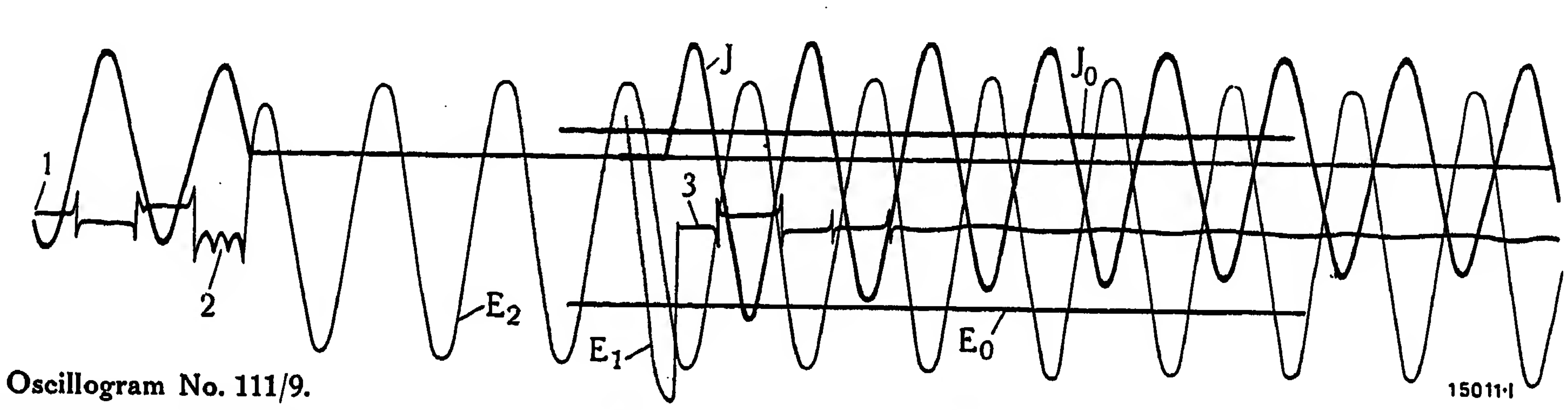


Fig. 32. — Closing and opening on a short circuit by a 12'000 kVA turbo-alternator with a 35'000 V circuit breaker.

J. Short-circuit current.
E_1. Potential before short circuit.
E_2. Potential after rupturing.
J_0. Calibrating current, $J_0 = 3900$ A.
E_0. Calibrating pressure, $E_0 = 3100$ V.
1. Commencement of the arc.
2. Tension across the arc while rupturing.
3. Tension across the arc when closing the breaker.

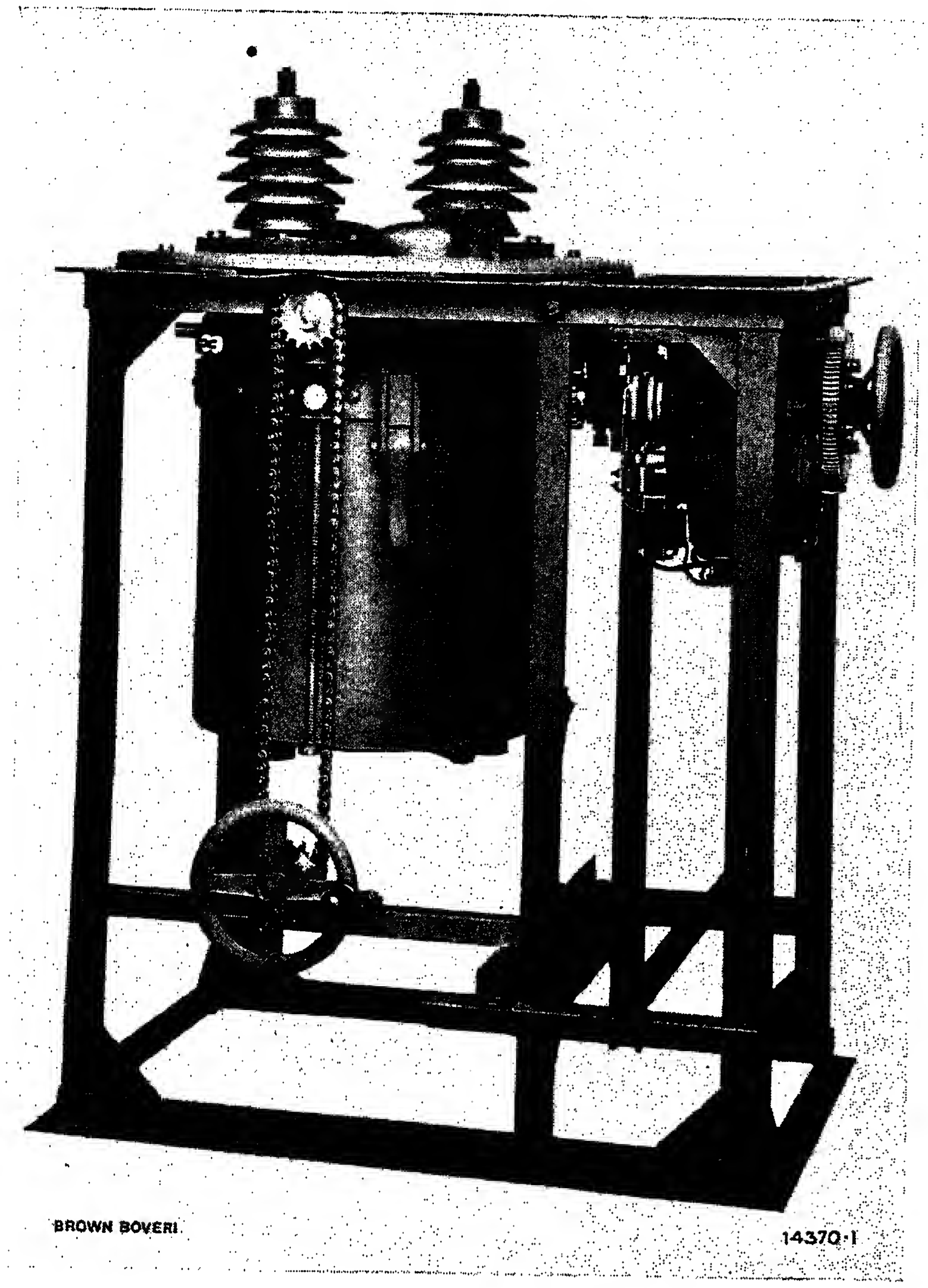


Fig. 33. — Single-pole oil circuit breaker for electric locomotives, 15'000 V, 350 A, with motor control, built-in current transformer, and resistance for transformer protection, mounted on a frame for testing purposes.

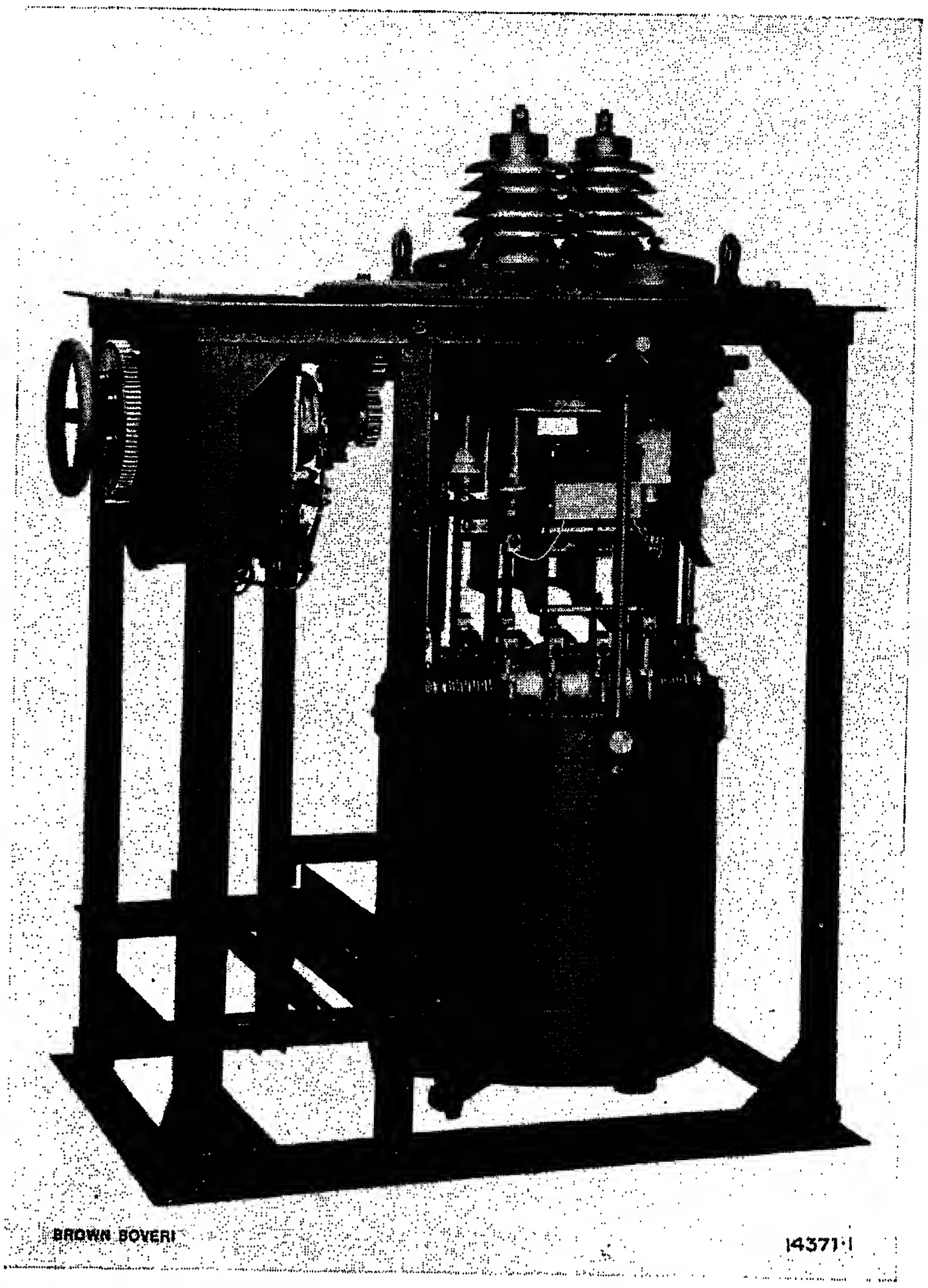


Fig. 34. — Single-pole oil circuit breaker for electric locomotives with oil tank lowered, 15'000 V, 350 A, with motor control, built-in current transformer, and resistance for transformer protection.

Duration of arc in half periods
(50 cycles) . . . . 4.
Arcing energy . . . . 400 kWsec.

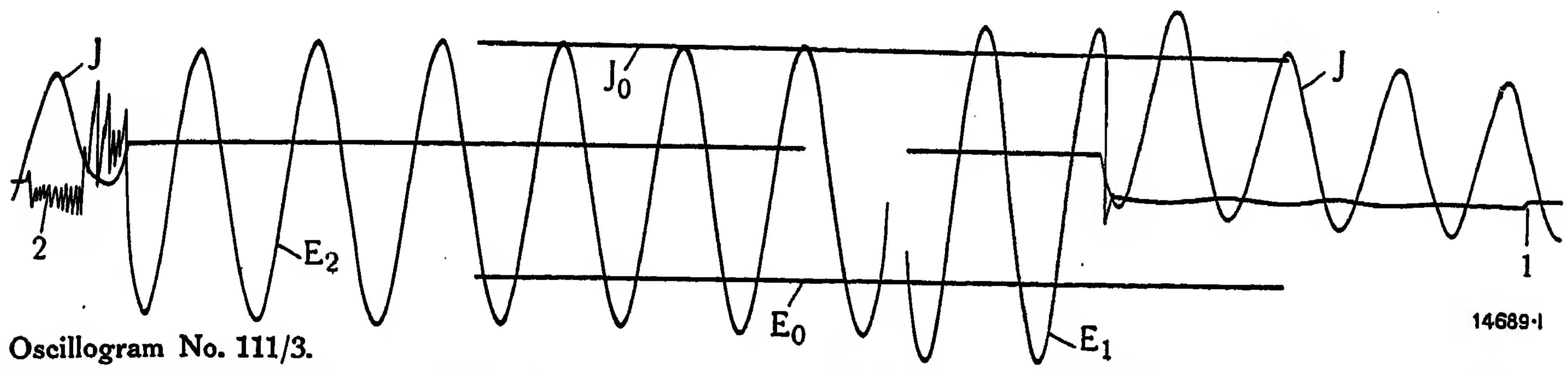
The length of the arc was only 3·5 cm. There was no excessive burning of the contacts, and the circuit breaker was still entirely serviceable at the conclusion of the tests.

The contacts first employed in this apparatus were found to have been separated by the electrodynamic forces resulting from the high currents. This effect was at times so great that when the breaker was closed on a short circuit, the current was actually interrupted again by the contacts coming apart. The latter occurrence is noticeable in the oscillogram 111/7 (Fig. 31). For this test, the operating gear of the circuit breaker was distorted in such a way that the main contacts did not touch, and the instantaneous short-circuit current was found to have been interrupted three times within 6 periods. The maximum peak value of the current was 25'000 A. When switched in on the short circuit (without immediately opening again), there was a distinct shock, expulsion of oil, and smoke, just as when interrupting a very heavy overload. In consequence of the arc formed through the contacts separating, some of the latter were fused together.

The experience made with this apparatus led to the design of a modified arrangement of contacts which was subsequently fitted to it.

II. Tests with a triple-pole circuit breaker, Type A 8/3, for 12'000 V. Among the tests made with this breaker were several when it was closed and opened instantaneously with a three-phase load of about 120'000 kVA, 10'300 V, 6600 A. This heavy duty did not damage it in the slightest or lessen its serviceableness. There was, however, a good deal of smoke, considerable throwing out of oil, and at times, flames were also noticeable.

During these tests, the breaker had neither an insulating lining for the tank, nor insulating plates between the contacts of the different phases.



Oscillogram No. 111/3.

Fig. 35. — Closing and opening on a short circuit by a 12'000-kVA turbo-alternator with a circuit breaker for locomotives.

J. Short-circuit current.
E_1. Potential before short circuit.
E_2. Potential after rupturing.
J_0. Calibrating current, J_0 = 20'500 A.
E_0. Calibrating pressure, E_0 = 3060 V.
1. Commencement of the arc.
2. Tension across the arc.

III. Tests with an oil circuit breaker as used for locomotives. The apparatus experimented upon in this case had a cylindrical, explosion-proof tank with a very substantial fixing device, insulating plates between the contacts, and also an insulating lining for the tank. The contacts were forced apart at first in this breaker too, but it was possible to overcome this effect by suitably modifying their arrangement. A series of switching-in and switching-out tests were made with pressures up to about 5500 V. Oscillogram 111/3 (Fig. 35) refers to one of these trials. The pressure here was 5500 V, the values of the current, etc. being the following:—

Maximum peak current about	30'000 A.
Current while rupturing	12'200 A.
Three-phase load while rupturing	200'000 kVA.
Duration of arc in half periods (50 cycles) .	3
Arcing energy	250 kWsec.

On every occasion, the various phenomena accompanying the operation of the circuit breaker did not exceed the permissible values. Its condition always remained such that it could be used again for regular service without overhauling, and there was so little burning of the contacts, that these did not even require touching up.

(d) *Testing an oil circuit breaker as used for locomotives with single-phase current, 16²/₃ cycles.*

An important foreign electric railway had tests made in a substation on circuit breakers of various makes destined for use on the locomotives. The apparatus furnished by Brown, Boveri & Co. was of the same design as the one with which the tests described in section 8c, III were made (see Figs. 33 and 34). The substation in question contained three transformers of 1600 kVA each, 80'000/15'000 V. These are fed from a power station with turbo-generating plant of 15'000 kVA through a double transmission line having a length of 40 km, and with a very small pressure drop.

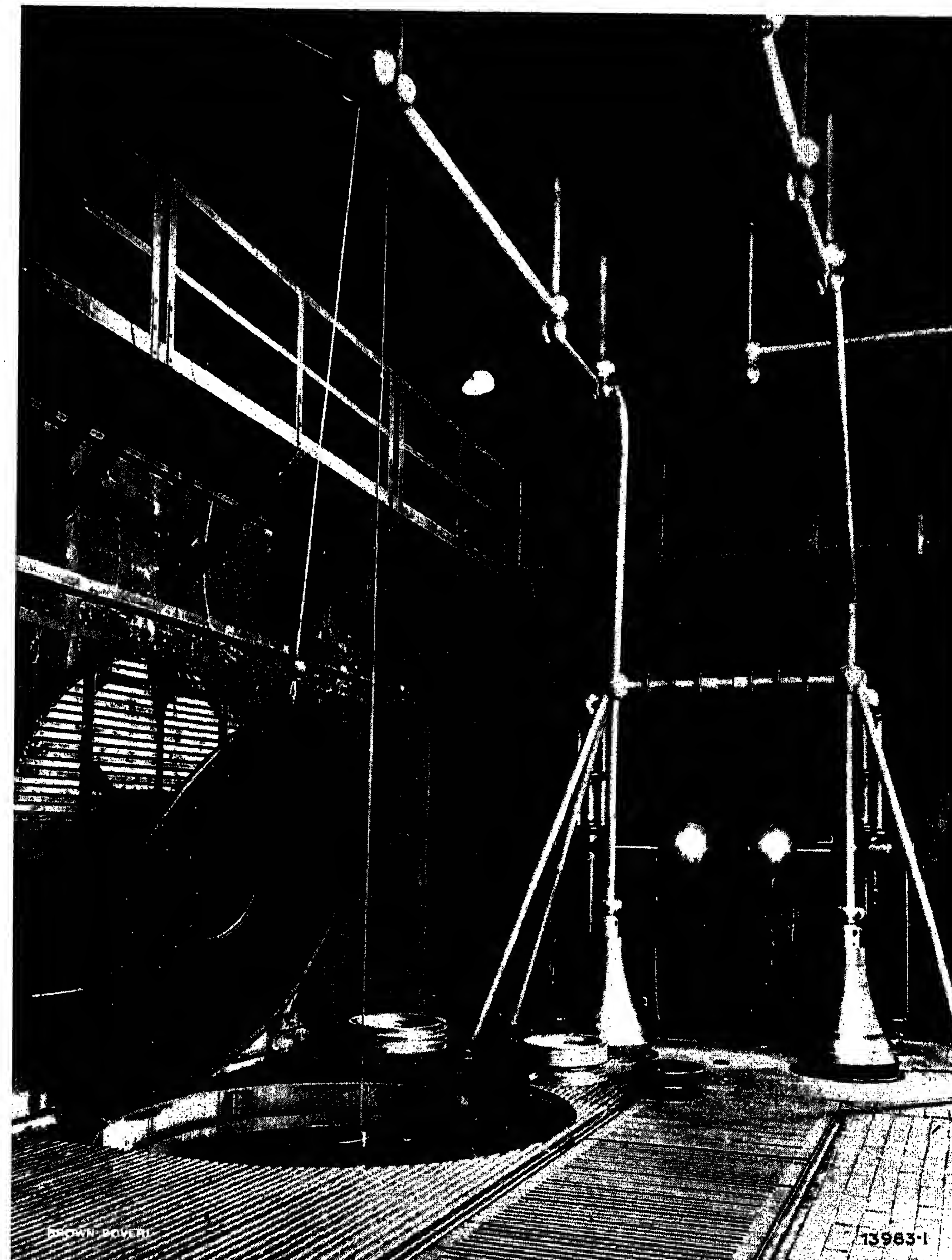


Fig. 36. — High-tension testing department, Brown, Boveri & Co., Baden.

The following tests were made:—

1. The short-circuit current was passed through the breaker; this has no noticeable effect.

2. The breaker was tripped by the short-circuit current with the relay set for opening instantaneously. The current was interrupted in this manner five times at intervals of one to four minutes. There was considerable vibration of the whole apparatus, which was mounted on a light framework; small puffs of smoke were expelled through the expansion valves; no oil was thrown out; the contacts were only slightly burned; and all parts remained perfectly intact.

3. The breaker was closed and allowed to trip instantaneously. This was done three times at intervals of one minute, the result being the same as with test 2.

In all cases, the circuit breaker was still in perfect working condition after the tests. The amount of burning at the contacts was so small that the apparatus could have been used for several times as many switching operations without requiring any attention.

The pressure for these experiments was 16'000 V, and the current while interrupting rose as high as 3250 A, which corresponds to a three-phase load of 155'000 kVA.

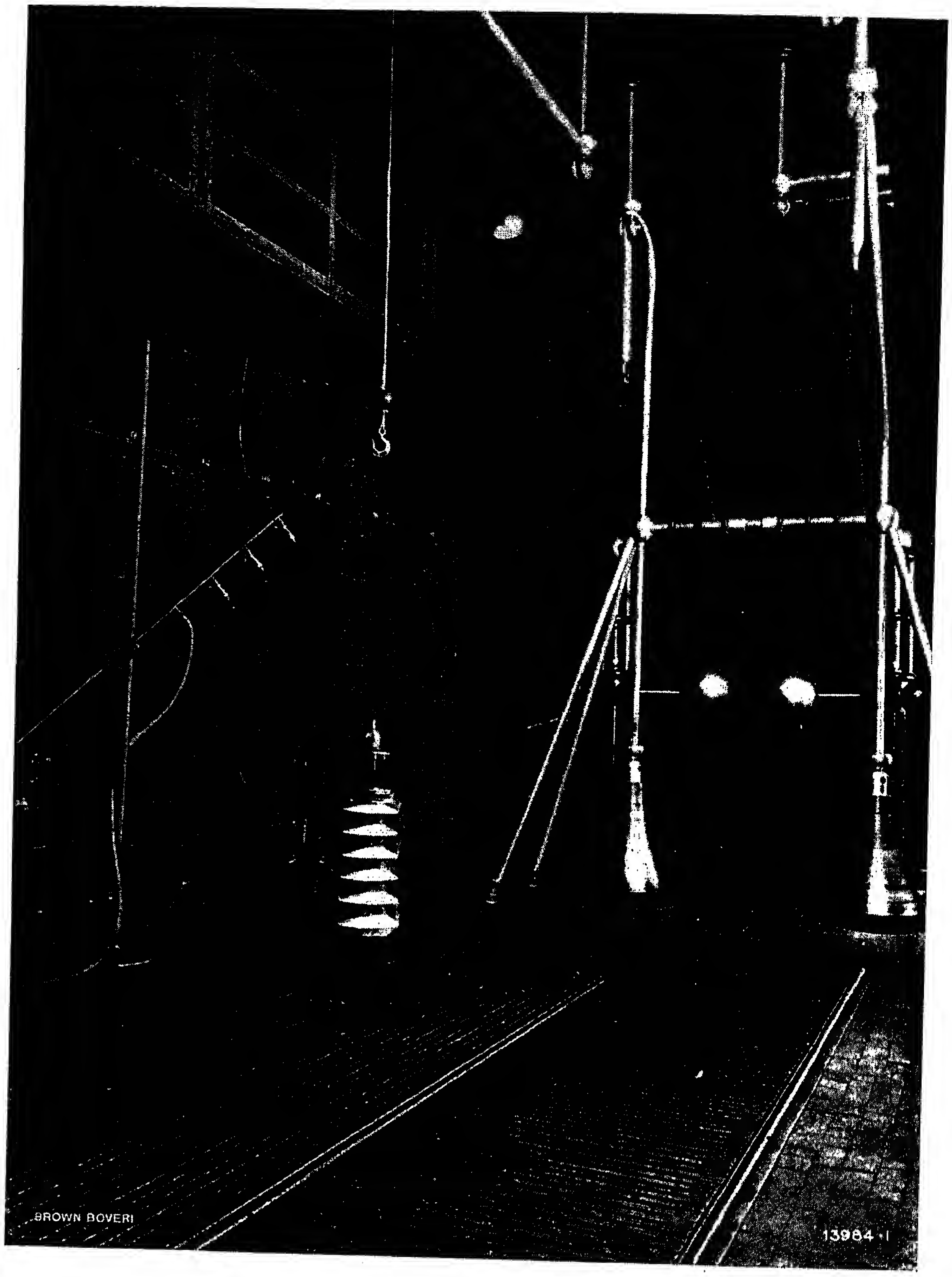


Fig. 37. — Flashover test on an oil-filled bushing for 11'0000 V in the high-tension testing department, Brown, Boveri & Co., Baden.

The Brown Boveri circuit breaker was the only one that stood up satisfactorily to several repetitions of this heavy duty — the breakers of other makes being all rendered unserviceable during the first trials. As a result, the Brown Boveri locomotive-type oil circuit breaker was adopted as standard by the railway in question for use on all the locomotives of various designs running on its system. The Swiss Federal Railways have also decided to instal the same type of Brown Boveri circuit breaker on all their electric locomotives, no matter by what firm they are supplied.

9. METHODS OF MOUNTING OIL CIRCUIT BREAKERS.

(a) In buildings.

The practice of dividing up switch rooms into single cells, each containing a set of switches, increases the safety of the installation, and is one that should always be followed in order to lessen the possibility of disturbances.

Even with circuit breakers that can interrupt the maximum short-circuit load with perfect safety, there is still the possibility of fires due to burning oil or explosions to be reckoned with. Such disturbances can arise from causes of quite secondary importance: main contacts in a bad state of repair may become overheated, and lead to ignition of the oil under certain circumstances; flashovers in the apparatus may result from water affecting the insulation or from a deposit of dust on the latter. Explosions can also be produced by the gases liberated when rupturing a normal short-circuit becoming ignited due to some cause not directly connected with the circuit breaker.

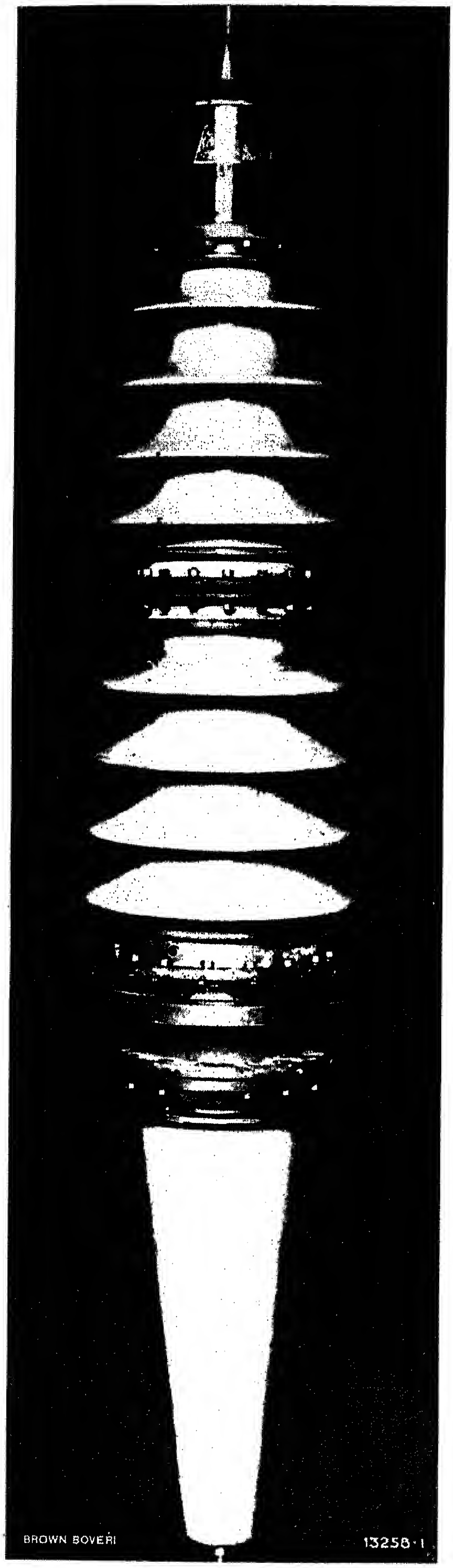


Fig. 38. — Oil-filled bushing for 150'000 V. Breakdown pressure in rain 300'000 V.

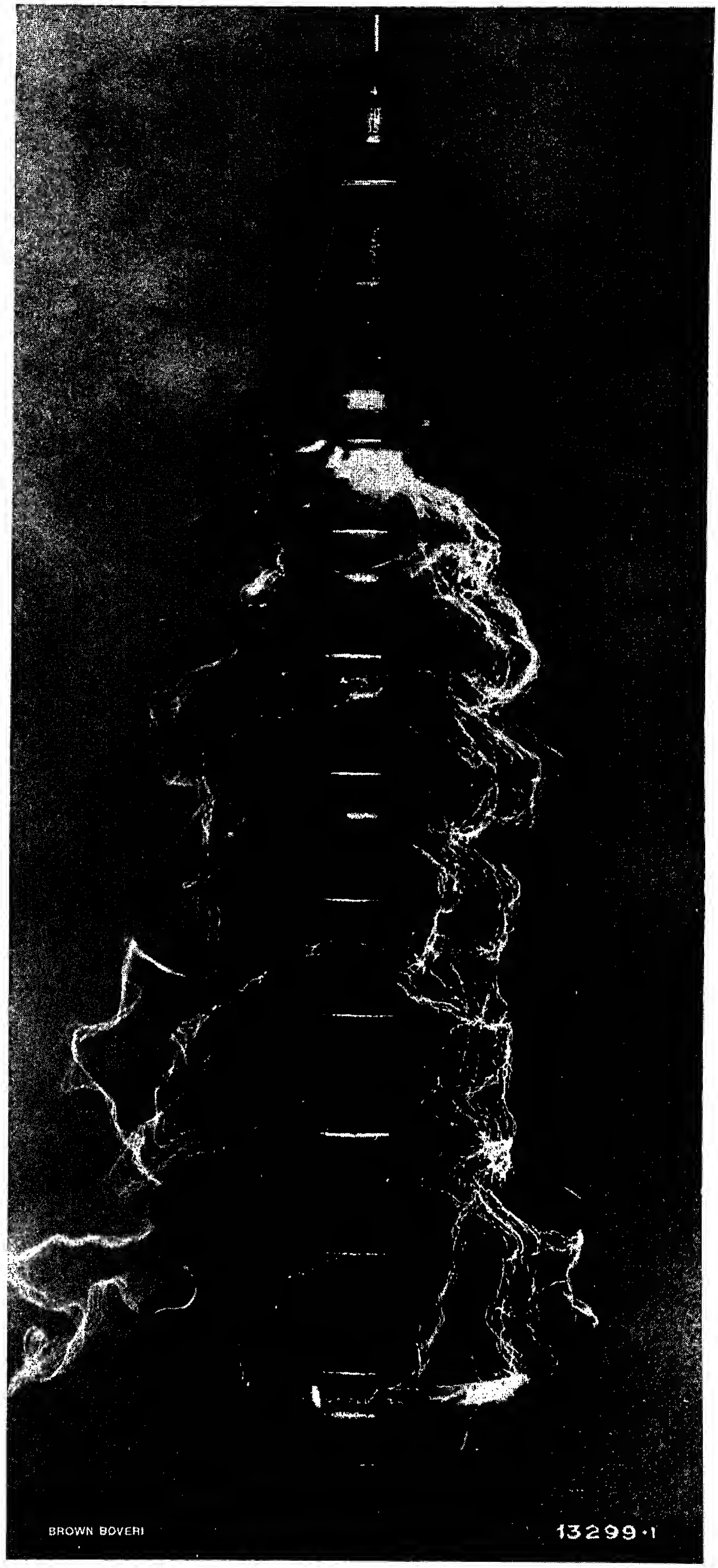


Fig. 39. — Oil-filled bushing flashing over at 280'000 V, with rain falling at the rate of 2·5 mm per minute.

The explosion gives rise to a certain increase of pressure in the cell containing the apparatus. As a rule, it is not possible to make the walls of the cell strong enough to withstand this pressure for a fairly long time, and it is consequently necessary to provide some arrangement for allowing immediate expansion. The iron expansion valves generally used for this purpose in the earlier days are insufficient, on account of their relatively large inertia. Brown, Boveri & Co. have therefore departed from the practice of fitting cells with such valves. They consider the best solution is to have the switch cells built at one of the outer walls of the building, and to provide in this wall large windows or weak sections of eternit at each cell. When an explosion occurs, these give way at once, and consequently a large opening to the outside atmosphere is provided.

The use of cells can be avoided altogether if the circuit breakers are made explosion-proof, and mounted in sheds as described hereafter under section c. This arrangement requires somewhat more space, since explosion-proof breakers are made practically only with cylindrical tanks and of the single pole types.

(b) In the open air.

Only in the case of extra high tensions is it as a rule economical to instal the circuit breakers in the open air. Against the reduction in the cost of the installation must be set the increased difficulty of attendance, and the fact that the apparatus is not protected from the weather.

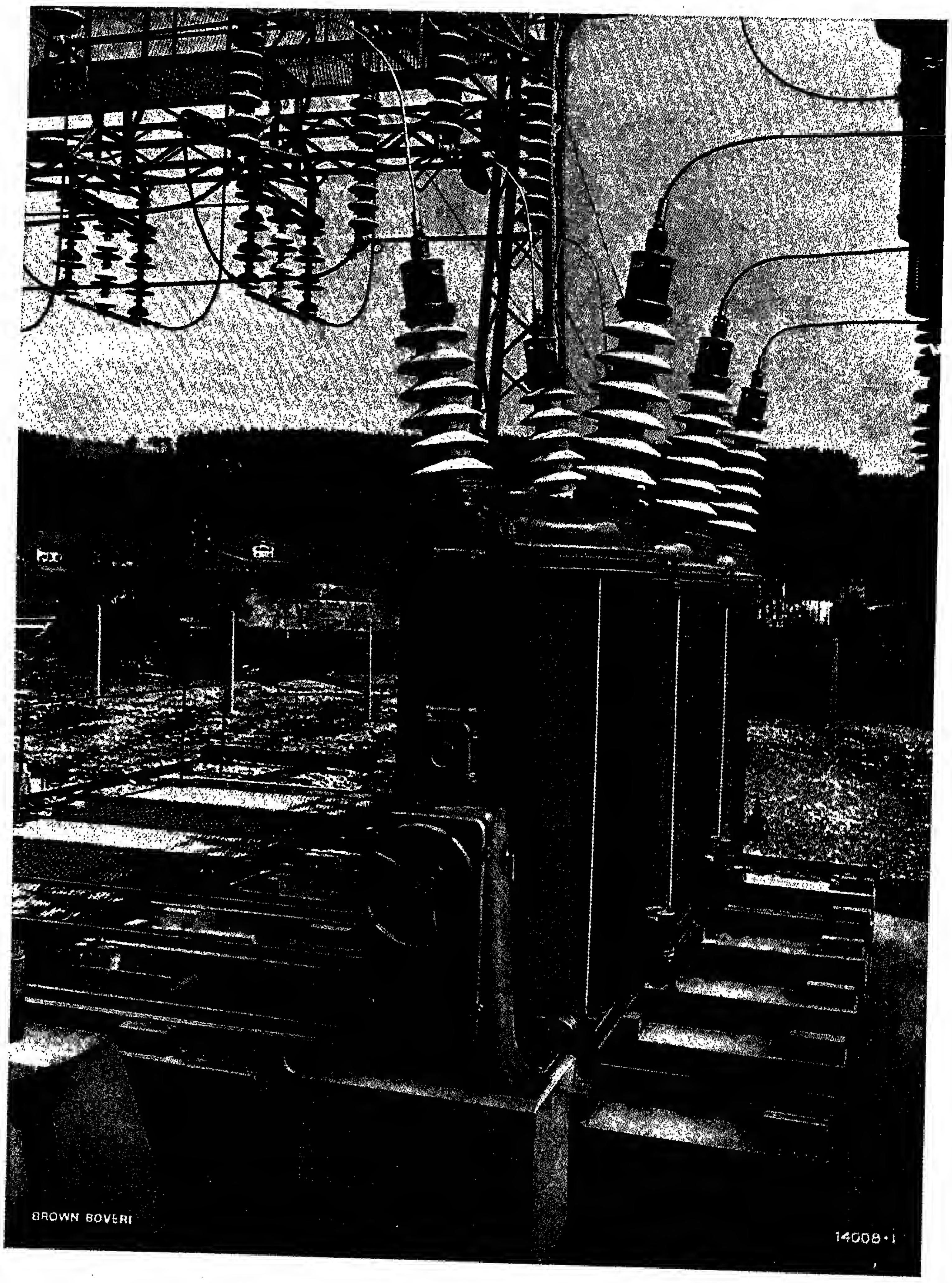


Fig. 40. — Set of three single-pole oil circuit breakers for 110'000 V in the Gœsgen outdoor substation, Swiss Power Transmission Co.

The circuit breakers, as well as the operating gear, auxiliary apparatus and connections of outdoor installations must be such that they are not affected by the weather. The bushings of the breaker terminals, in particular, must be of sufficient size to prevent flashovers from taking place when it rains. For this reason, oil-filled bushings (Fig. 38) have been adopted. A 110-kV Brown Boveri oil circuit breaker for outdoor use is shown in Figs. 8 and 9, a 150-kV breaker of similar type in Figs. 14 and 16, and the inside of the operating pillar is seen in Fig. 15. Fig. 40 shows a group of three oil circuit breakers for 110 kV in the outdoor station at Gœsgen of the Swiss Power Transmission Co. (Schweizerische Kraftübertragungs-A.-G.).

As the circuit breakers in outdoor plants are subjected directly to the frost in winter, it may be necessary to provide special electric heating apparatus to prevent the oil from setting.

(c) In open sheds.

To avoid the principal drawbacks of open-air stations without going to the expense of providing regular switch rooms, Brown, Boveri & Co. have suggested placing the circuit breakers in sheds. The tanks of the apparatus are buried in the ground, the lids made explosion-proof, and vents provided for leading off any gases that may be generated. No partitions or walls of any kind are required, so that supervision is easy, while the use of expensive bushings, as are necessary in switch houses for high-tension current, is avoided.[1]

[1] See Elektrotechnische Zeitschrift, 1922, p. 1142.

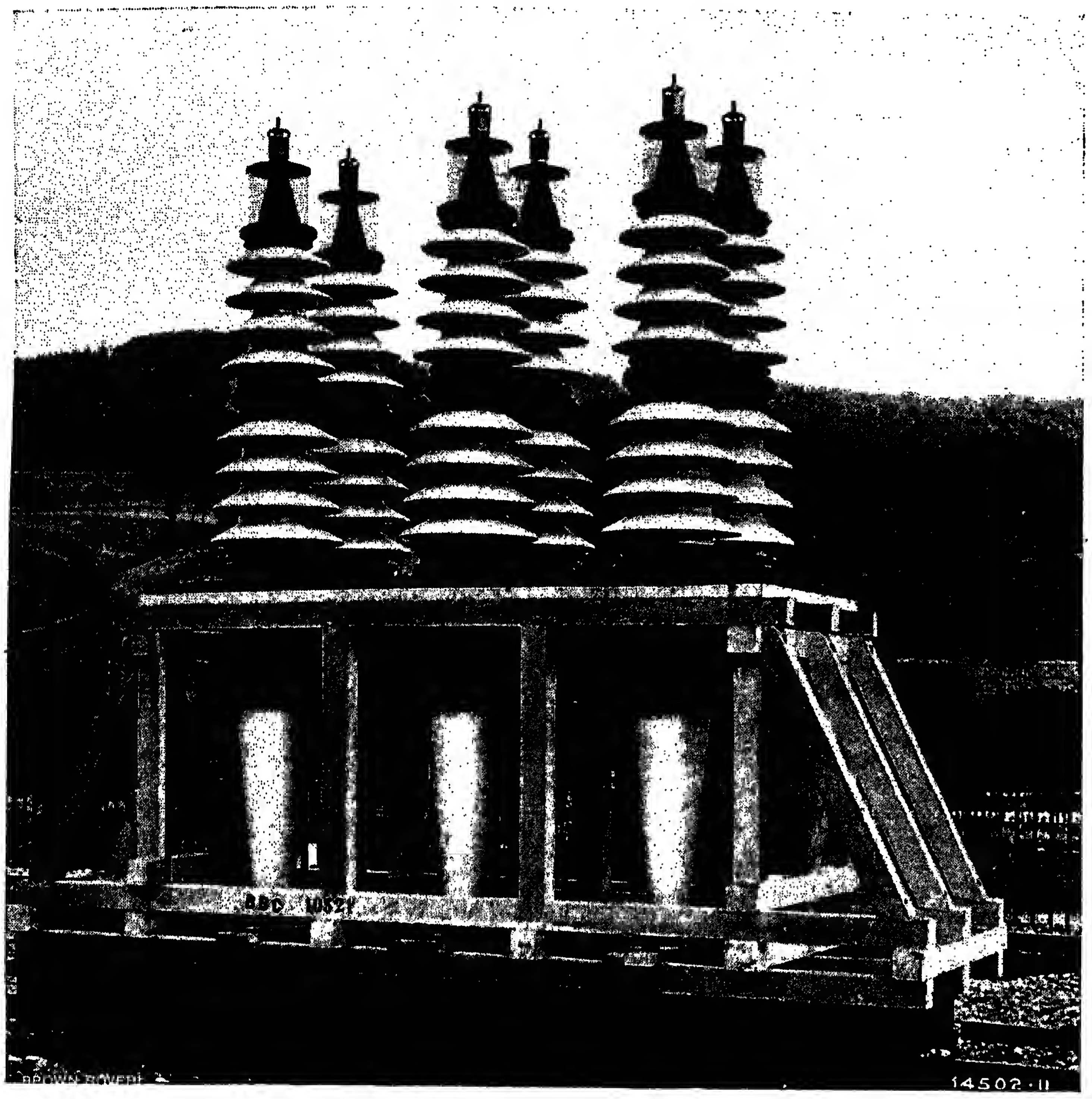


Fig. 41. — Porcelain bushings for 15'000 V, single-pole, outdoor-type oil circuit breakers, ready for dispatch.

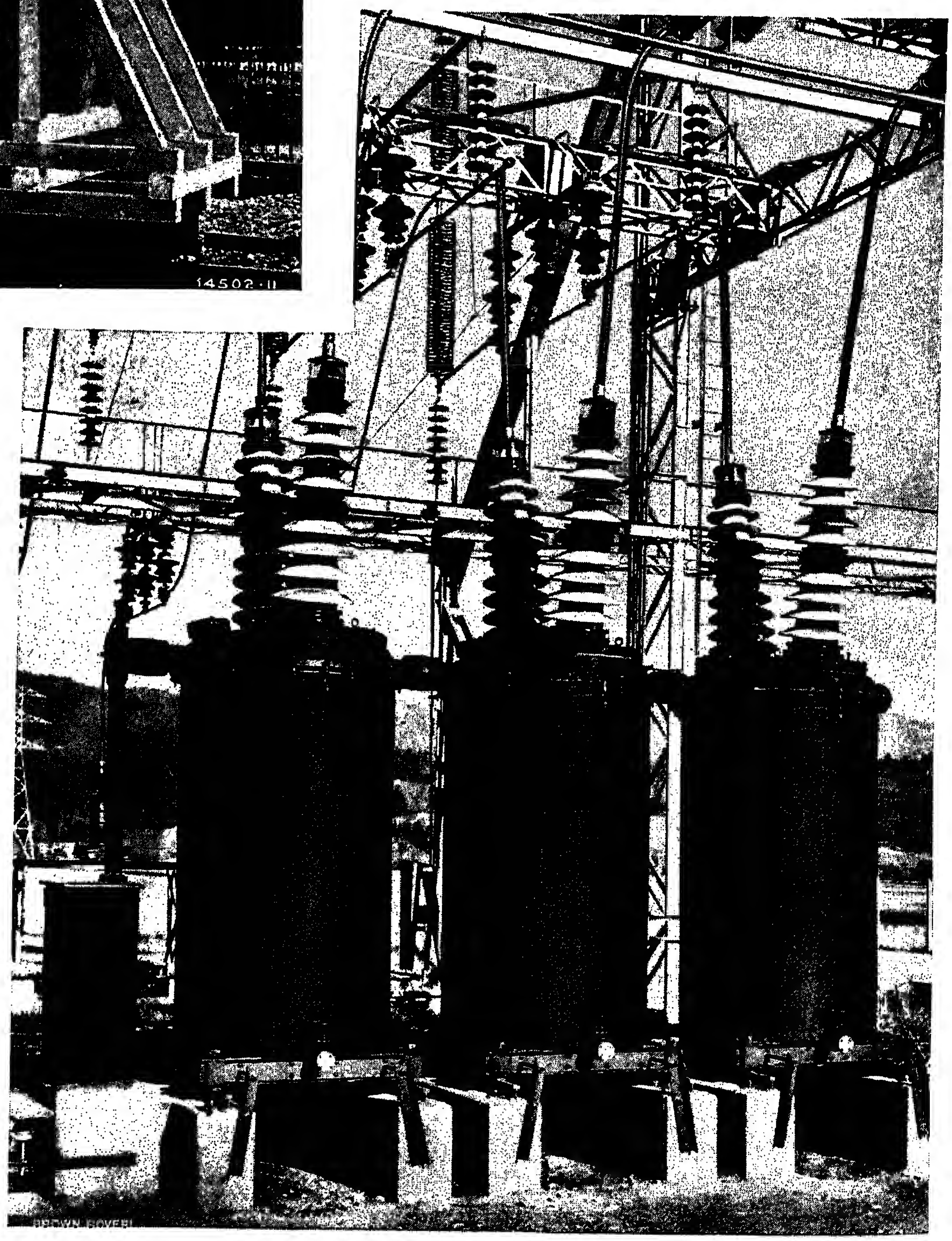


Fig. 42. — Set of three single-pole oil circuit breakers for 150'000 V in Bassecourt outdoor substation, Bernese Power Works, Berne.

10. SUMMARY OF THE PRINCIPLES ON WHICH THE DESIGN OF BROWN BOVERI OIL CIRCUIT BREAKERS IS BASED.

The most important principles for the design of Brown Boveri circuit breakers, as based on the result of wide experience and numerous tests, are briefly the following:—

(a) The use of more or less numerous breaking points according to the tension.

(b) Welding the tank in such a way that it has the maximum strength to resist internal pressures.

(c) Insulating lining for the tank and insulating partitions between the different contacts.

(d) Employment of contact springs with a large initial compression.

(e) No other insulating material than oil between the contacts of the same pole when the breaker is open.

(f) Ample depth of oil above the contacts.

(g) Possibility of fitting resistances for breaker protection — this is especially recommendable when very heavy currents have to be interrupted.

(h) Possibility of fitting resistances for transformer protection without diminishing the rupturing capacity of the breaker — this should be done whenever switching operations are undertaken on large transformers at no load.

(i) Protective resistances for transmission lines that are switched in and out unloaded can probably be dispensed with in all cases by employing circuit breakers with several breaking points.

G. Bruhlmann. (J. F. L.)

Fig. 43. — Three single-pole oil circuit breakers, 150′000 V, 350 A, loaded ready for dispatch in the yard of Baden Works, Brown, Boveri & Co.
In the middle are the three oil tanks with the control pillar. The cases to the left contain the various interior parts, that to the right contains the complete bushings.

NOTES ON THE TRANSPORTATION OF HEAVY TRANSFORMERS.

Decimal index 621. 314. 3 : 355. 27.

IN an article which appeared in the Revue BBC, 1921, No. 2/3, an account was given of the transportation of heavy transformers, and of the use of modern lifting tackle in such cases. The following descriptions, which are completed by a number of photographs, give an idea of the difficulties encountered when transporting very heavy transformers weighing as much as 32 tons apiece.

Fig. 1 shows a three-phase transformer of 7000 kVA weighing 22 tons, for the Birsbrucke substation of the Basle electricity supply. A well wagon was used to convey it from the goods station at Wolf to the above substation.

The chief difficulty consisted in bringing safely to destination a transformer over three metres wide on a lorry having a width of only one metre. Lateral swaying of the transformer was prevented by propping it up with two wooden shores on each side, which were fastened to the tank by ropes, as can be seen in Fig. 1. During the one-and-a-half-hour journey, one or two men kept these shores clear of the ground by swinging them outwards, and put them down immediately the transformer began to sway, thus ensuring perfectly safe transportation. These shores came in very useful when the driver once tried to turn the lorry somewhat carelessly. The transformer would almost certainly have slid off the wagon and overturned, but for shores, which took up their duty instantly. Fig. 2 is a photograph recording this event. Powerful winches, however, enabled the transformer to be righted again in a very short time, and the journey was accomplished without further incident.

The transportation of three 3000-kVA three-phase transformers, each weighing 18 tons, for the Monthey works of the Society of chemical Industry, Basle, presented many interesting features (Fig. 3).

The local conditions, particularly the roads leading to the transformer station, left no other alternative open other than to convey the transformer in the railway wagon up a specially-prepared incline. A substantial timber scaffolding carrying two

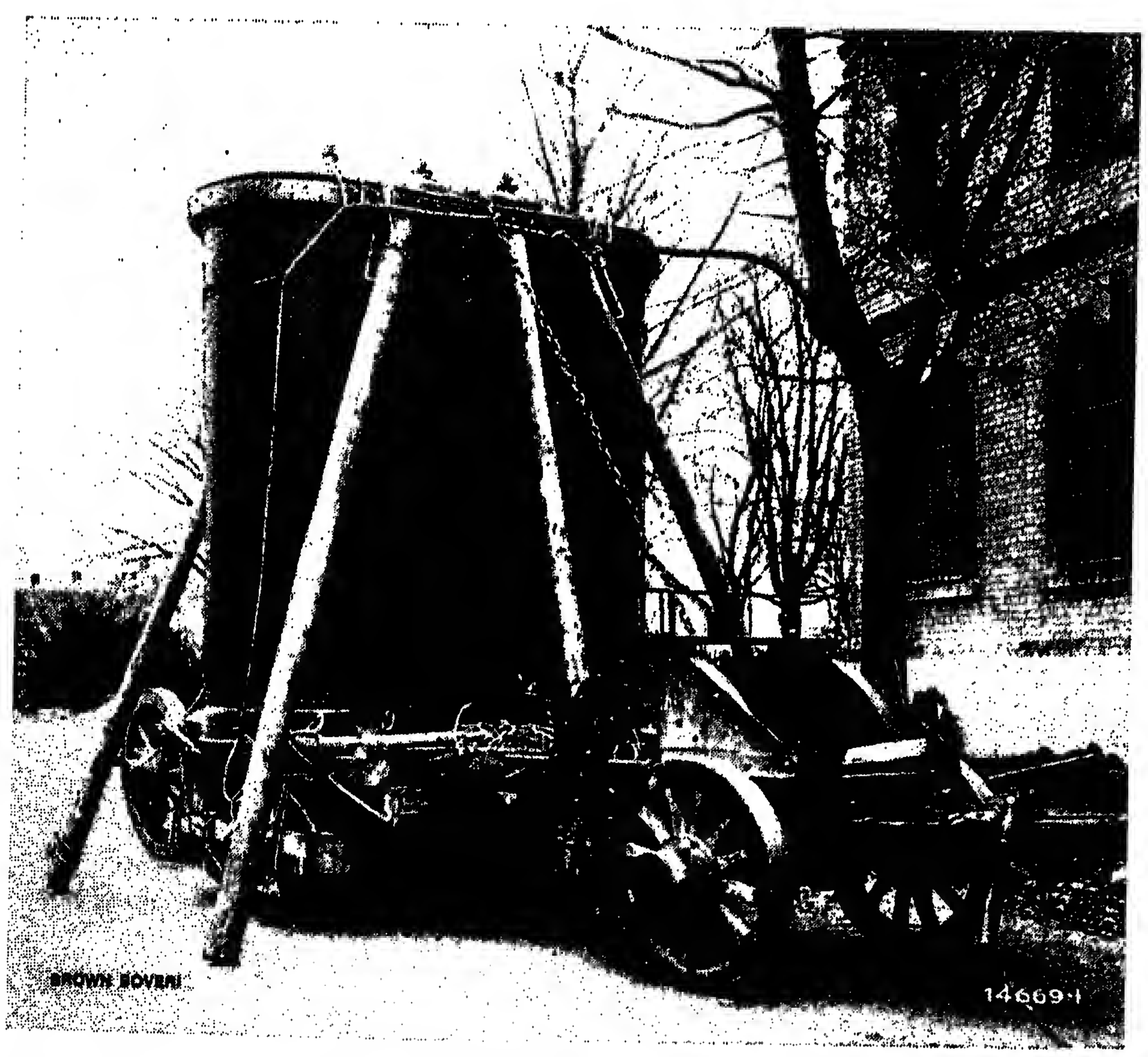


Fig. 1. — 7000-kVA transformer ready for transportation on a well wagon.

Fig. 2. — An incident during transportation of the 7000-kVA transformer from Basle railway station to Birsbrucke substation.

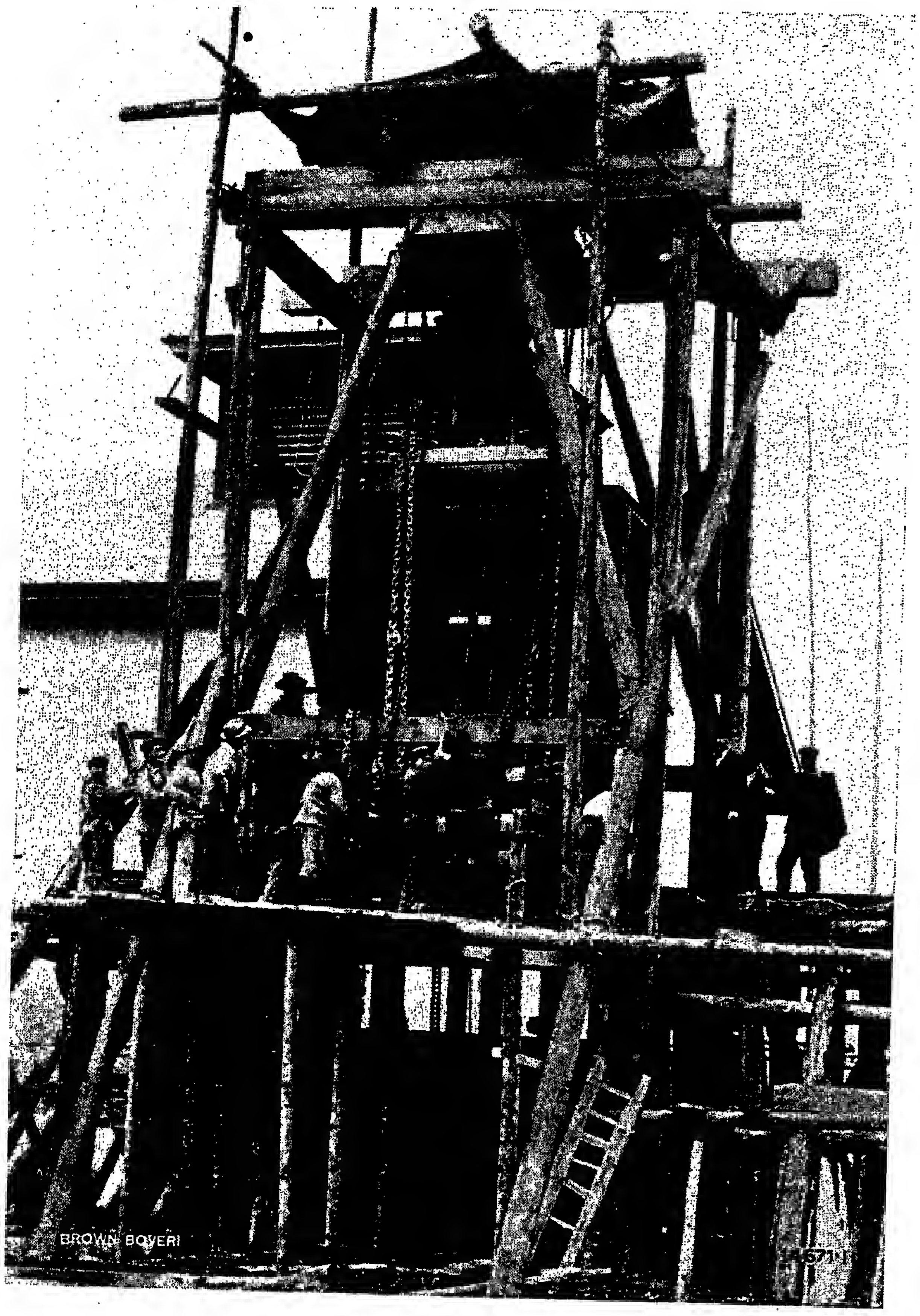


Fig. 3. — Transportation of a 3000-kVA transformer to Monthey.

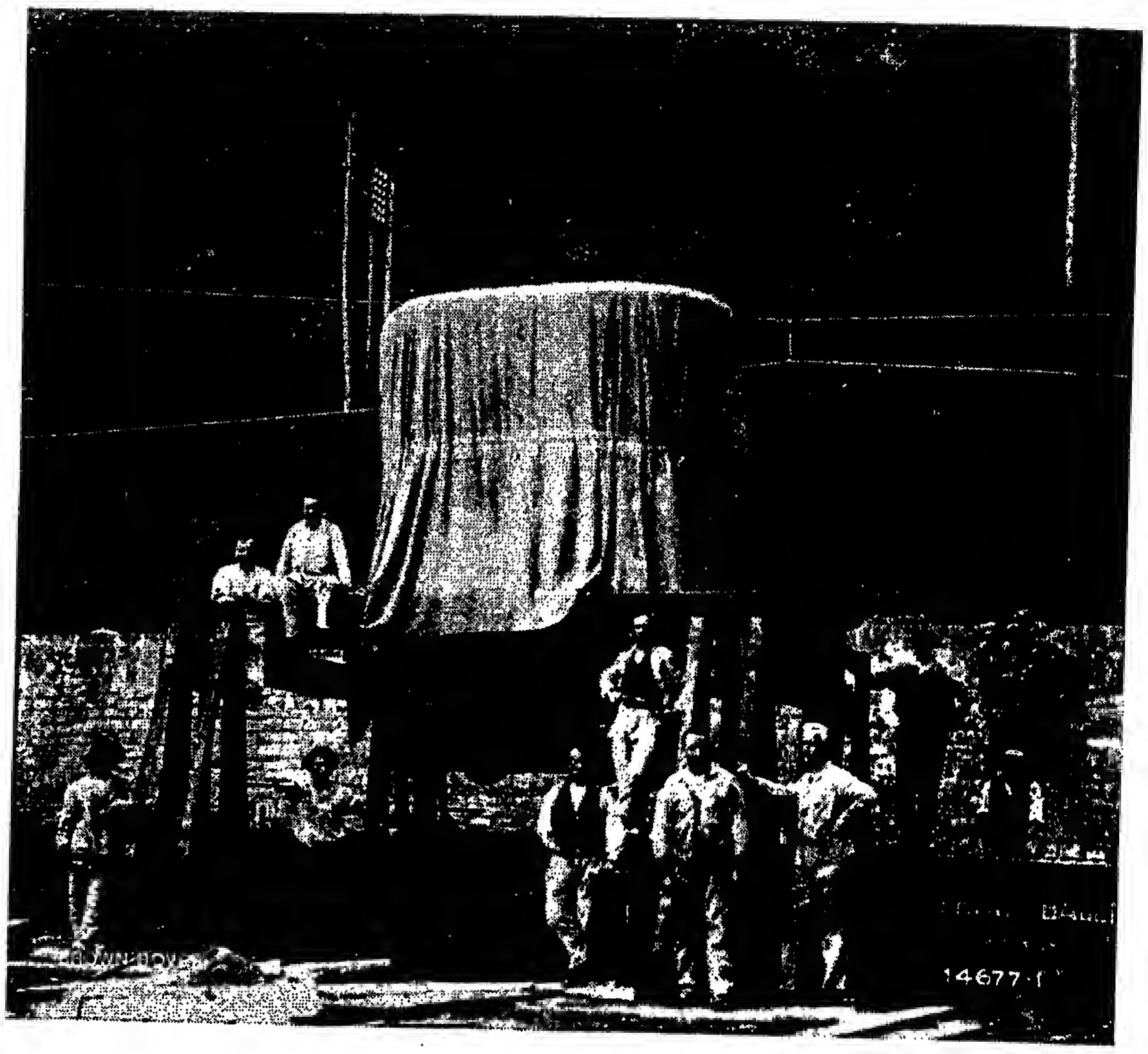


Fig. 4. — Unloading a 5000-kVA single-phase transformer at Melide substation, Swiss Federal Railways.

10-ton pulley blocks permitted the transformer to be lifted out of the truck, and then lowered on to the ground. Only then was it possible to bring the transformer into its cubicle.

Another case where several knotty problems had to be solved was that of transporting three three-phase transformers of 5300 kVA each to the Jogne works of the Entreprises Electriques Fribourgeoises, Fribourg (Switzerland). The weight of one of these transformers amounts to 15 tons. Fig. 5 is a photograph taken while transferring the first of them at Bulle station from the wagon of the Swiss Federal Railways to one belonging to the narrow-gauge Gruyère Railway.

Apart from the jacks and cross beams necessary, rails were used as longitudinal supports. Four wire ropes passing under the axles of the carrying rollers enabled the transformer to be lifted. The standard-gauge wagon was then removed, and its place taken by the narrow-gauge one. Attention may be drawn the fact that one of the rails is common to both gauges. The transformer was then conveyed from Bulle to Broc on the above-named narrow-gauge railway, whence it had to be transferred to a strong well wagon for

Fig. 5. — Unloading a 5300-kVA transformer at Bulle station prior to transferring it to the Gruyère Railway.

road transport. Fig. 7 shows the transformer lifted from the wagon. A framework of timber and iron beams was prepared for receiving the transformer, and for bringing it to its assigned place in the power station with the help of a rope winch.

For the electrification of the St. Gothard Railway, a substation has been erected at Melide, which is similar to that at Giornico. Two 5000-kVA single-phase transformers weighing 32 tons apiece are installed in this station. The conditions for unloading are considerably more favourable than at Giornico, as a special line branches off from the main railway track, so that no restrictions are imposed by the traffic on the time taken for unloading. Consequently, no extensive preparations were necessary to carry out this work. The jacks rested on substantial timber supports — an arrangement which enabled the the transformer to be lifted high enough for its removal in special truck. An extremely laborious operation was to turn the transformer 90°, so as to bring its longitudinal axis at right angles to that of the truck. After the removal of the lifting takle, the transformer was brought into its cubicle. Fig. 4 shows the transformer after it had been lifted off the railway wagon.

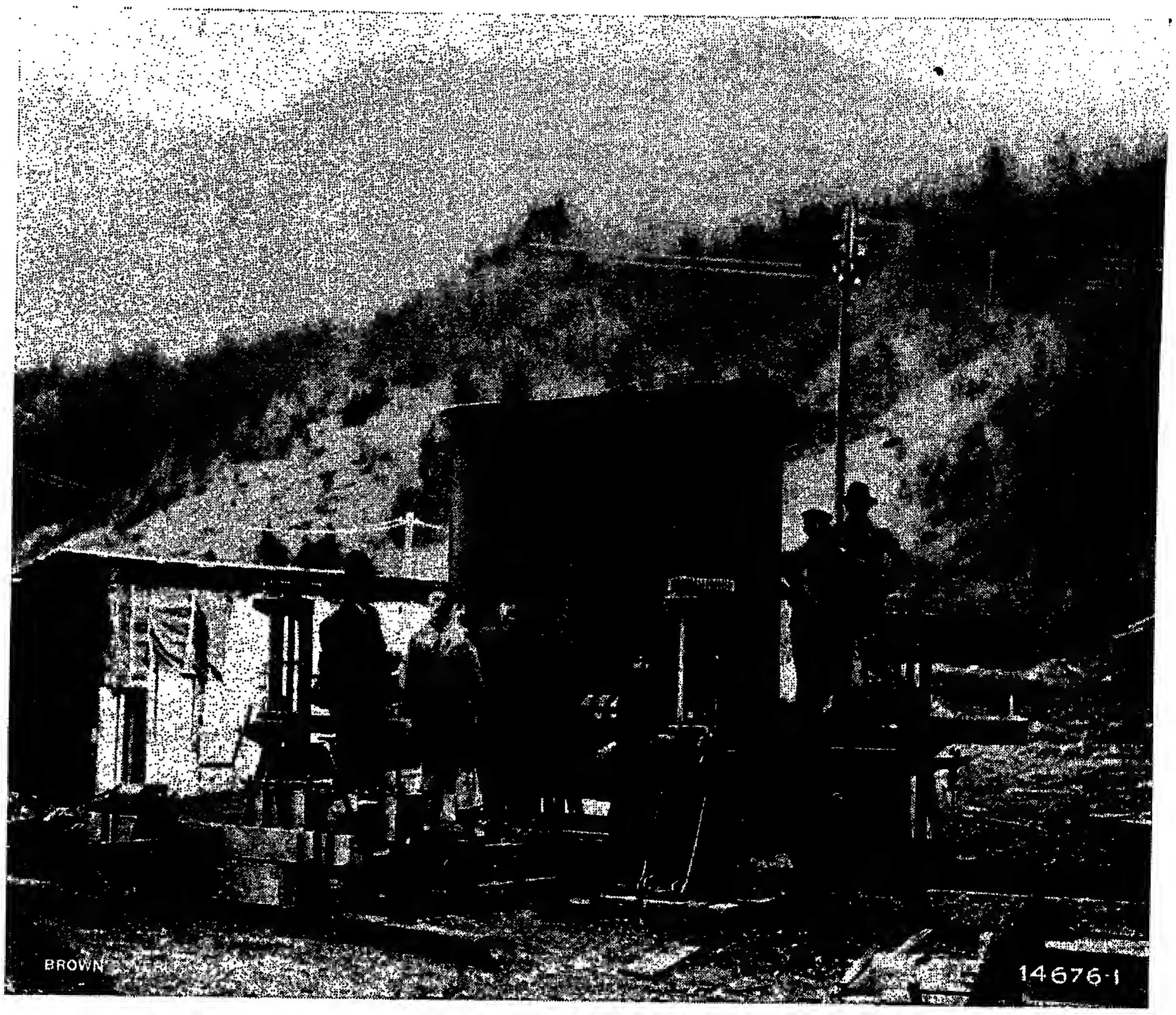


Fig. 7. — Transferring the transformer from well wagon to transporting platform.

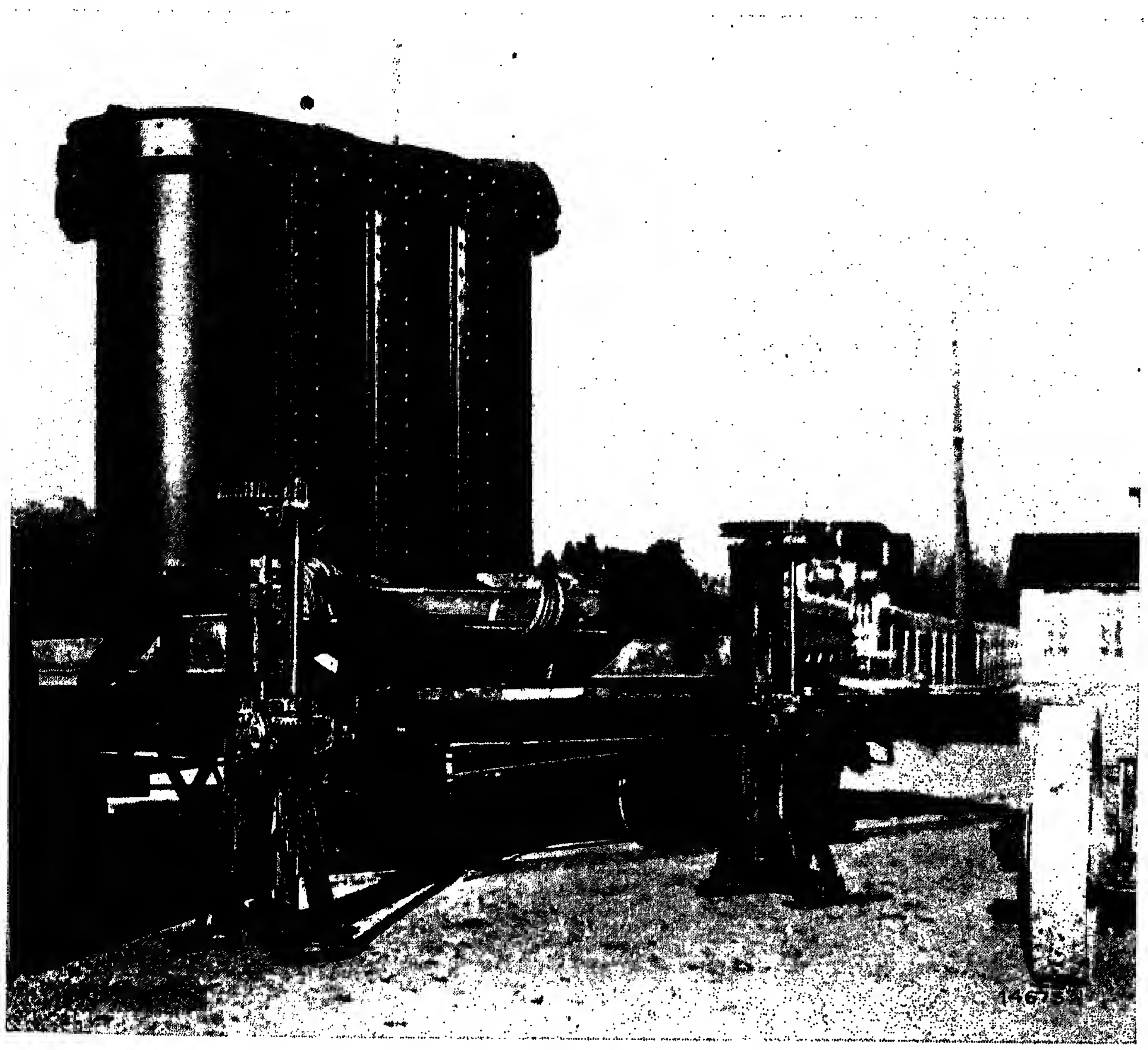


Fig. 6. — Unloading a transformer from a narrow-gauge wagon prior to transportation by road.

In conclusion, it may be mentioned that the instances of transportation which have been briefly outlined, were accomplished without any serious mishaps, despite the difficulties encountered.

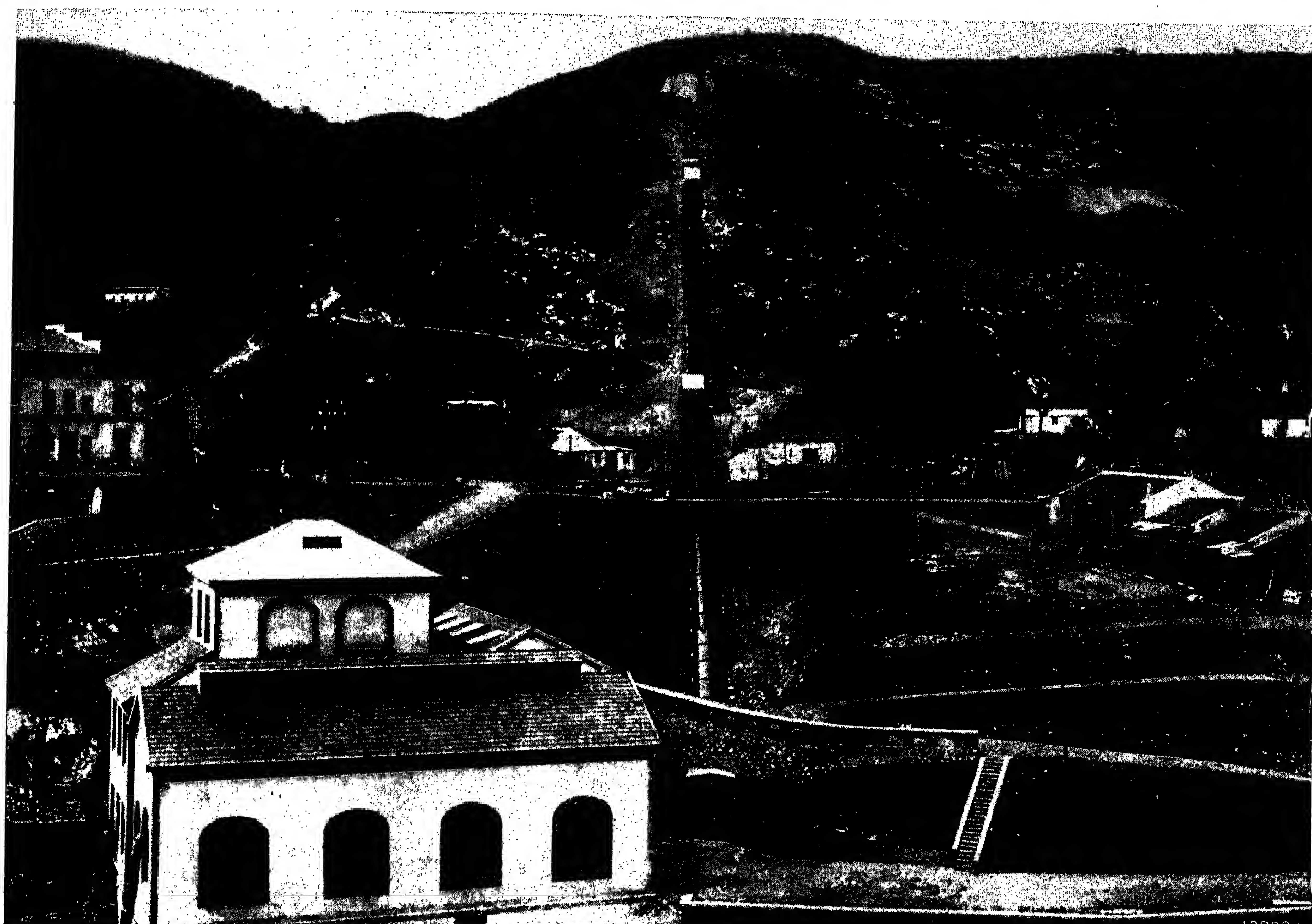
O. Steiger. (D. M.)

Published by BROWN, BOVERI & CO., BADEN (Switzerland). Printed by Kreis & Co., Basle.

VOL. IX JANUARY, 1922 No. 1

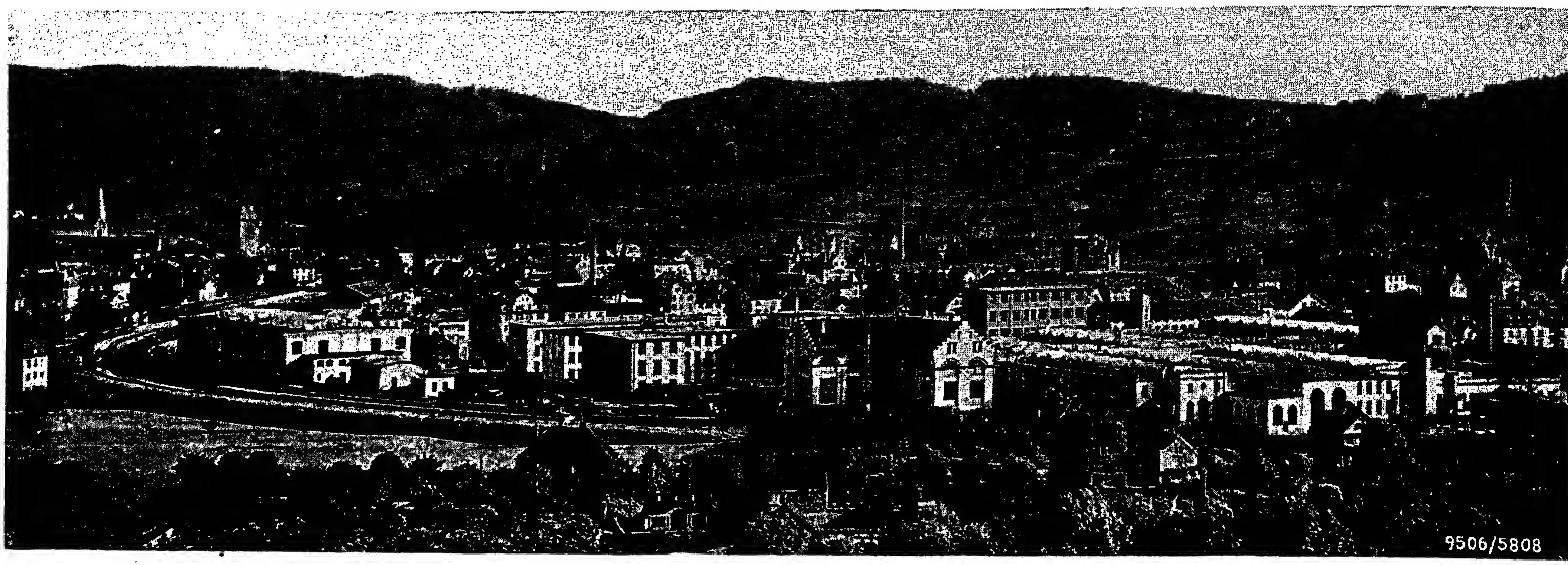
THE BROWN BOVERI REVIEW

EDITED BY BROWN, BOVERI & CO., BADEN (SWITZERLAND)



VIEW OF THE BUITRERAS POWER STATION ON THE RIVER GUADIARO, SPAIN,
Showing, penstock and surge tank.

CONTENTS:



BADEN WORKS.

THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & CO., BADEN (SWITZERLAND)

VOL. IX JANUARY, 1922 No. 1

The Brown Boveri Review is issued monthly. Single numbers: 1.20 francs (1 shilling). Yearly subscription: 12 francs (10 shillings).

THE present issue inaugurates the English edition of our monthly technical journal. This will be uniform with the French and German editions which have appeared regularly for the last eight years. It will contain technical articles of general interest and descriptions of our manufactures. On account of the uniformity of the three editions it may happen that the first few numbers contain articles, each complete in itself, but belonging to a series begun in last year's French and German editions. In such cases we shall indicate the issues in which such previous articles appeared and gladly forward copies, in French or German as desired, as long as our stock lasts.

THE BUITRERAS HYDRO-ELECTRIC POWER STATION ON THE RIVER GUADIARO.

Decimal index 621. 312. 134.

THE Guadiaro is a river in the south of Spain which flows into the Mediterranean near Gibraltar. Owing to the nature of the hydrographical basin of this river, which is a region bearing a meagre and sparse vegetation, the character of the river is, to a marked degree, that of a mountain torrent. By this is meant that the maximum discharge is many times greater than the minimum. Thus the discharge of the Guadiaro varies between 20 cubic feet per sec in the dry season and 20 000 cubic feet per sec when the river is in flood.

The "Sociedad Hidro-Electrica del Guadiaro" obtained a concession from the Spanish Government some years ago to use the two principal falls on the river, which are those of Corchado and of Buitreras. The first, a fall of 370 feet effective, was turned to account 15 years ago, and the power station in question (Corchado) has been in continual service since that time. Owing to various difficulties met with, arising for the main part from silting up, which had a marked influence on service conditions during the flood periods of 1917 when the Guadiaro carried over 23 400 cubic feet per sec, the company decided to alter and enlarge the head works and flumes. This work was carried out during the war in combination with the equipment of the lower fall, that of Buitreras, which is also of about 370 feet effective head.

Fig. 1. — Buitreras Power Station, Showing tail race.

The hydraulic works and the building of the power house itself have already been described in detail in articles by Mr. Adolph Weber, which appeared in the "Revue Polytechnique Suisse" on June 4, 11 and 25, 1921, to which the reader is referred. These articles, however, describe only the hydraulic works in detail and contain no complete description of the turbine and electrical equipment of the power house proper. As the electrical equipment of the latter incorporates a number of new and most interesting features a short description of the equipment will be of interest, although, the Revue BBC, 1917, No. 6, p. 136, has already given a general survey of the plant. Before beginning a description of the plant in detail a summary of its principal characteristics will be useful.

The electrical equipment of the power house, built to meet the requirements of the first period of service, is as follows: —

(a) Two three-phase vertical shaft generators each built for 3000 kVA, 5000 V, 50 cycles, power factor 0·75, 750 r.p.m., with built-on exciters. These generators are of the enclosed type provided with ducts for the inlet and outlet of the cooling air. They are direct coupled to water turbines built by Escher, Wyss & Co., Zurich.

(b) Two three-phase oil-immersed transformers each 3000 kVA, 5000/52 000 V. These transformers are of the water-cooled type, with inside water cooling, and are provided with a special device to protect the windings from the effect of short-circuits.

(c) Auxiliary equipment composed of a station transformer of 50 kVA, a motor-generator set giving 25 kW on the D. C. side, and an accumulator battery.

(d) A switchboard composed of generator panels, outgoing line panels, one set of 5000 V auxiliary bus-bars, and one 52 000 V set of main bus-bars (to which are connected the alternator transformer sets and the two outgoing 52 000 V lines), the auxiliary panels for reserve excitation and for station service, the lightning arresters and accessories.

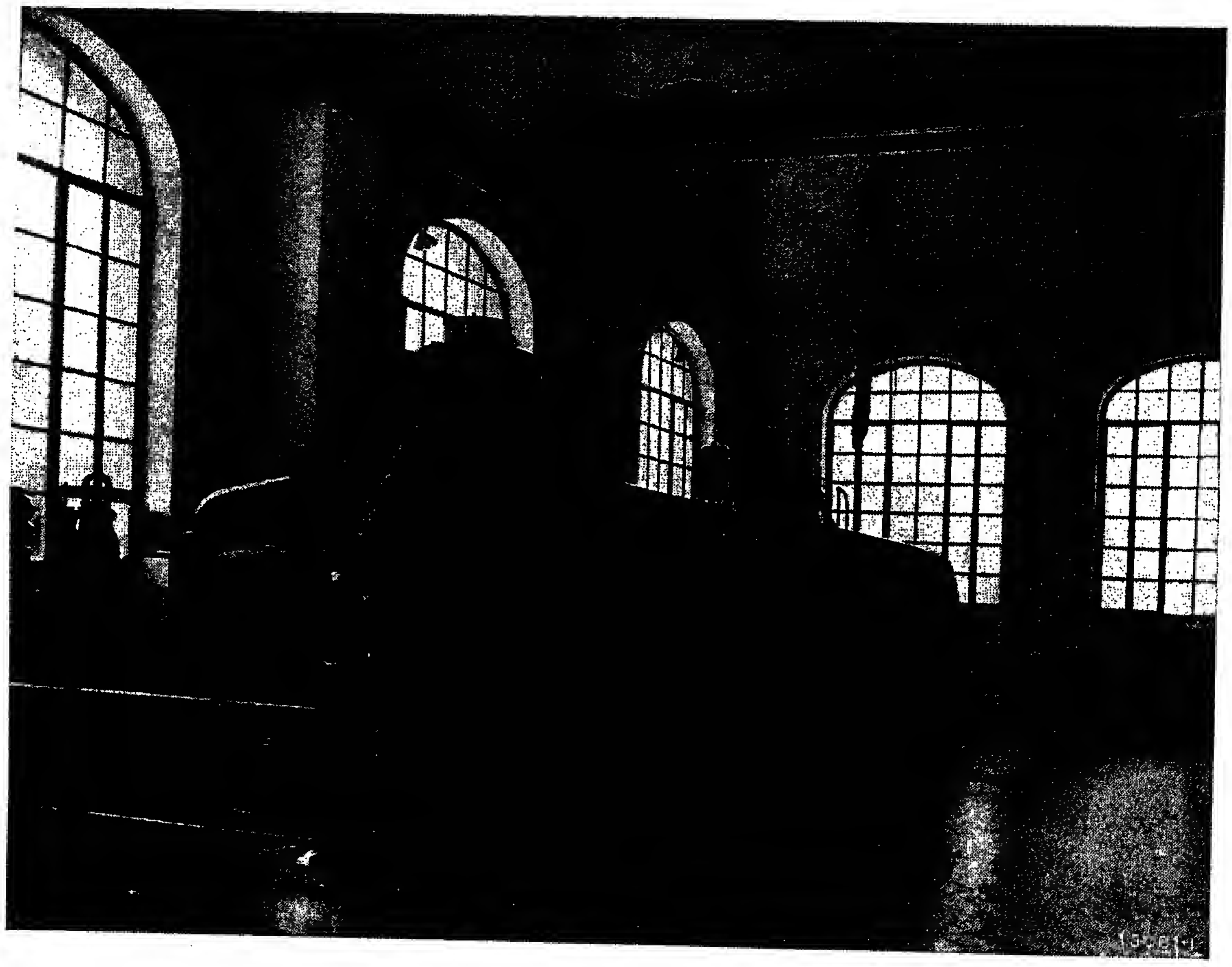


Fig. 2. — The generators of the Buitreras Power Station.

ALTERNATORS AND EXCITERS.

The three-phase alternators with built-on exciters were delivered, along with the transformers and switchgear, by Brown, Boveri & Co. of Baden. These alternators are designed for the following conditions: —

Continuous output: 3000 kVA on an inductive load with a power factor of 0·75, that is 2250 kW.

Driving power required at the shaft: 3250 HP.

Pressure: 5000 V; this can be raised to 5500 V at a reduced load of 2700 kVA.

Frequency: 50 cycles. Speed: 750 r.p.m.

Flywheel effect: 6000 kgm².

The alternators are built with vertical shaft, two guide bearings and base plate. The shaft carries a forged coupling flange which is bolted to a similar flange on the shaft of the Escher Wyss turbine. The exciters are built on.

The technical guarantees met by the generators are the following: —

Efficiency, including excitation and ventilation losses as well as friction losses in the two guide bearings: 95·5 % with a 3000 kVA load and at unity power factor, 94·0 % with a 3000 kVA load and 0·75 p. f.

Margin: 15 % of the total measurable losses.

The losses are calculated by the separate losses method and in conformity with § 41 of the rules of the Association of German Engineers (V. D. E.).

Temperature rise. After continuous operation under full load of 3000 kVA with p. f. 0·75, the temperature rise of the various parts of the machine is at least 10° C below the limit values set by § 18 of the rules of the V. D. E. The temperature of the surrounding air is taken as being 45° C.

Overload capacity. This is in accordance with the rules of the V. D. E.

Excitation. The power required for excitation, under the most unfavourable conditions of load and power factor to be met, is not more than 25 kW at 110 V.

The heaviest weight for erection is 8500 kg, this being the pole wheel with the shaft. The heaviest weight for transport is 6000 kg. Each complete generator with its exciter weighs 27 500 kg.

The design is shown clearly in Fig. 4 and can be described shortly as follows: —

The pole wheel is built up of a number of Siemens Martin steel rings shrunk on to the shaft. This design has the advantage of allowing close inspection of the material during construction, because the various rings have to be machined all over. The internal tension in the shrunk-on steel

rings is about equal to that produced in the rings when the generator reaches run away speed. This makes it impossible for the rings to work loose if the turbine should accidentally run away.

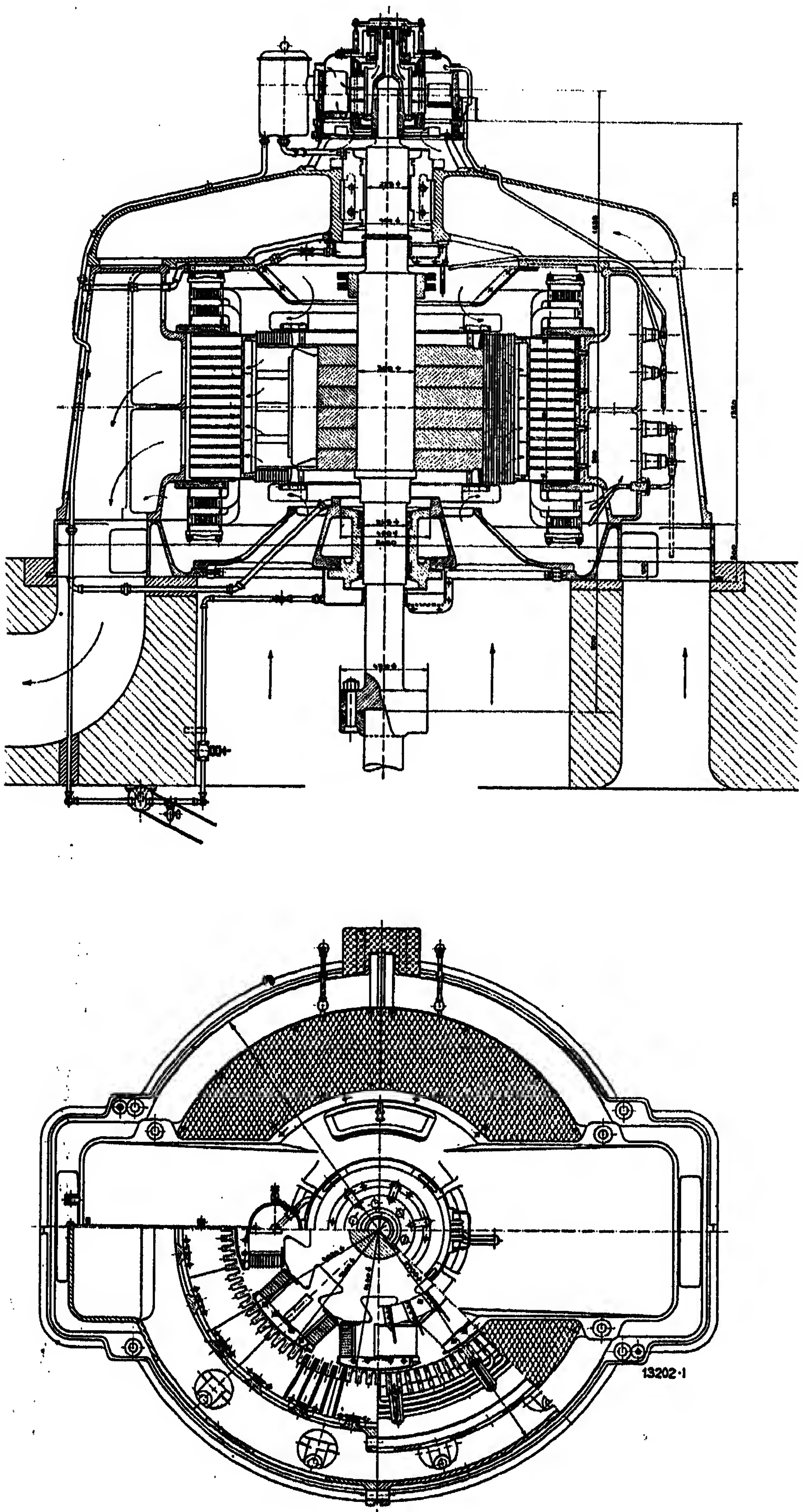


Fig. 3. — Three-phase generator in the Buitreras Power Station (3000 kVA, 5000 V, 50 cycles, p. f. 0·75) with vertical shaft and built-on exciter.

The poles, themselves of cast steel, are massive and crowned by laminated pole shoes. The poles are fastened on the rim by dove-tail slots, very exactly machined and with all angles rounded.

After completion the pole wheel is statically and dynamically balanced so that the machine is free from vibration at all loads. It can, further, stand for a short period the increase in speed which takes place if the regulator of the turbine be accidentally put out of action. This runaway speed of the turbine is 1350 r.p.m. and the alternator pole wheel is tested in the shops at this speed for a period of 5 minutes.

The shape given to the pole shoes is such that the higher harmonics which are caused by the variations of the magnetic flux, according to the position of the pole with regard to the stator slots, are negligible. Further, the pole shoes are laminated so as to reduce as far as possible the eddy currents caused by unequal flux distribution due to varying reluctance of the teeth. The shoes are skewed, which reduces the amplitude of stator teeth harmonics.

The profile of the pole shoe has been designed so that the form of the pressure wave is practically sinusoidal.

The method of fastening the poles on the rim has the great advantage of allowing the removal of each pole separately, which is done axially with the help of a special device. This is necessary when the stator coils have to be repaired or replaced.

The field coils are formed of copper ribbon wound on edgewise and insulated between successive layers by presspan rings. They are insulated from the pole core by a presspan cylinder. Each coil is axially compressed by means of a pressure ring bolted

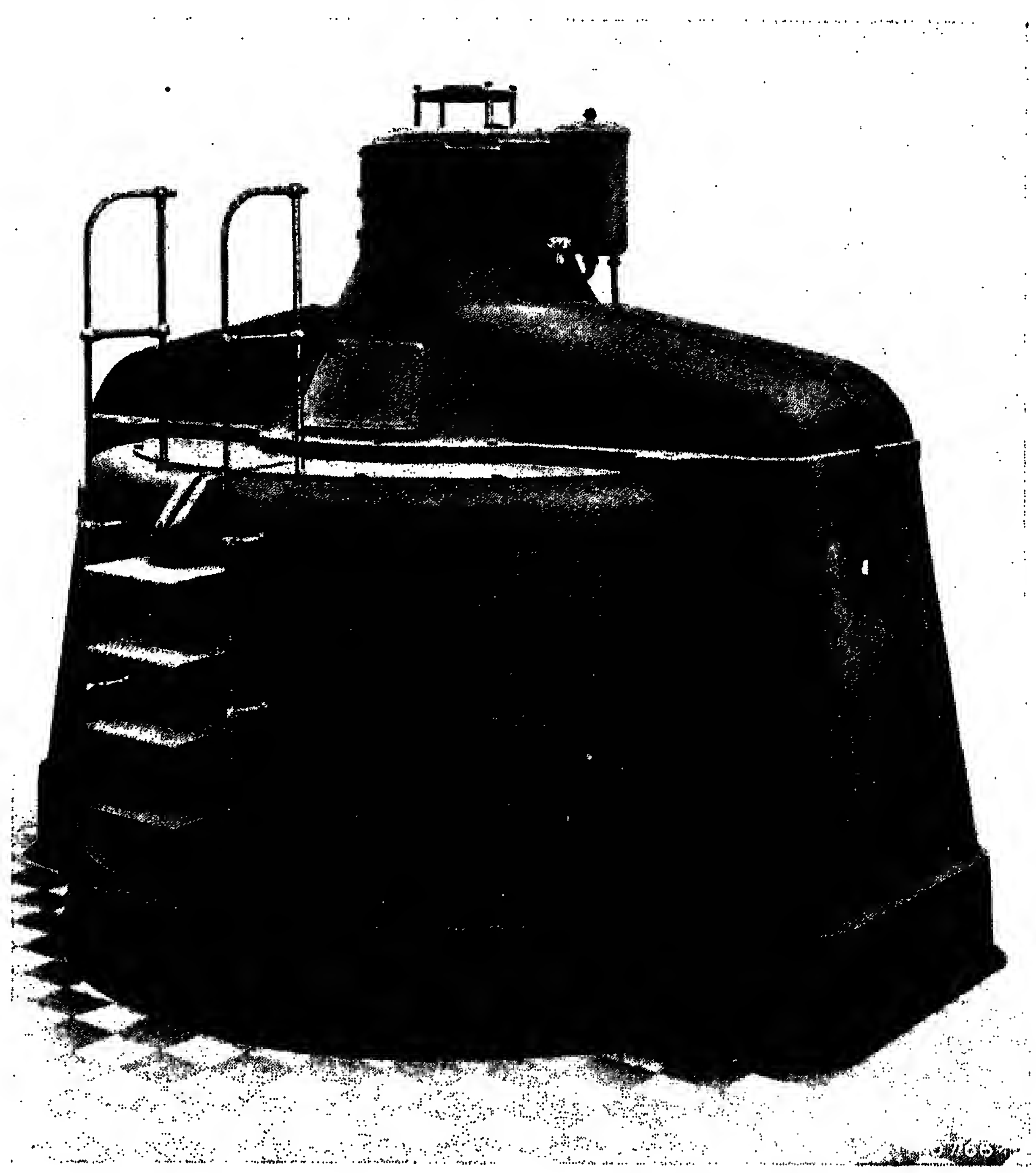


Fig. 4. — Three-phase generator in the Buitreras Power Station (3000 kVA, 5000 V, 50 cycles, p. f. 0·75) with vertical shaft and built-on exciter.

on to the pole shoe, so that the pole and coil form a whole which cannot be deformed.

The collector rings of the alternator are of steel, shrunk on to a cast iron hub, from which they are separated by an insulating micanite ring. The current is led to the rings through a number of carbon brushes. The shaft is of Siemens Martin steel of very best quality. In order to avoid internal stresses in the metal, the shaft was first forged and then reheated to a dull red. The shaft has a forged coupling flange at the turbine end. The total weight of the complete rotor, amounting to 8500 kg, is carried by the footstep bearing mounted on the turbine and delivered by the turbine builders.

Stator. The stator frame consists of a substantial iron casting in two parts, inside of which the stator core is fitted. This is composed of sheet-iron laminations with paper insulation and held in position by means of dove-tail grooves through which run iron rods bolted to the casing. Clamping plates on either side ensure sufficient compression of the laminations. The stator teeth are, further, compressed from without by means of pressure fingers forming part of the above mentioned clamping plates. The whole laminated core is subdivided axially into numerous sections separated from one another by special spacing pieces so as to form ventilating ducts. In this way the stator has a very large cooling surface. The slots are of the open type, which is not only advantageous for constructional reasons but has the advantage of making the replacing or repair of coils an easy matter.

The alternator is enclosed at both ends by cast iron end shields. These shields fulfil two purposes: — they protect the coil heads and connections from accidental damage, and they guide the flow of cooling air along the most advantageous circuit. The coil head connections are carried by brass supports which press them against the outside plate of the active stator core. The connections are, therefore, wedged against the outside of the stator core and are, further, supported from the stator frame by means of insulating distance pieces. The arrangement is such that no deformation of coil heads or connections need be feared in the event of a short circuit. For removing or replacing the stator winding, or part of the winding, it is only necessary that one or two poles be removed from the pole wheel in the manner described before; the stator slots are then accessible and the stator coils can be taken out.

The stator coils are former-wound and composed of superimposed layers of copper of rectangular section insulated one from another and covered by micanite sleeving.

Each coil is impregnated thoroughly in special insulating compound and then that part of the coil which lies in the stator slot is covered by a sleeve of compressed mica moulded on. The coil heads and connections are insulated by Empire cloth.

The guide bearings are of the usual type provided with water cooling. The latter is not necessary under normal conditions, but was added as a measure of precaution. The upper bearing is carried by arms radiating inwards and forming a spider, the lower bearing being supported on a framework bolted to the base frame of the machine. The bearings are of white metal of best quality in cast iron bushes. They are provided with a spiral copper tube to allow of water cooling, as explained above.

Lubrication is carried out by gravity, oil dropping from an upper reservoir through tubing into the guide bearings. The oil collects after passing through the bearings, and is then pumped through a filter and back into the upper reservoir. The oil pump in question is belt driven from the shaft of the turbine regulator.

General design and ventilation. The alternator is carried on a rigid base frame, anchored by holding down bolts to the masonry. This frame carries the weight of the stator only, as the foot-step bearing of the turbine carries the whole weight of the rotating part of the set. The alternators are completely enclosed, ventilation being carried out by means of cooling air drawn in from below and a cold air duct leading from the basement to the upper part of the alternator through one of the supports of the stator. Thus cold air enters the machine from above and below.

After cooling the stator windings, this air is driven, by suitably arranged vanes on the pole wheel, against the inside periphery of the stator and radially outwards through the air channels provided between the sections of the stator core. On reaching the outside periphery of the stator the heated air is carried away through a hot air duct placed diametrically opposite the cold air duct. The forced draught ventilation thus obtained is most efficient without being noisy.

The design of the alternator is such that these two air ducts cast on the outside of the stator frame in no way detract from the pleasing lines of the machine.

Exciters. The built-on exciters are of standard design, with commutation and regulation poles. The latter permit stable operation of the exciter at low

voltages and thus a very wide range of alternator tension regulation can be obtained by means of the exciter field rheostat alone. The latter is provided with a large number of steps so that a fine adjustment of the alternator tension is possible. No alternator main field rheostat is necessary.

This design of regulation poles was patented by Brown, Boveri & Co. some years ago and has given complete satisfaction in all plants and for units of very large output. The elimination of main field rheostats was universally recognised as a welcome simplification, not only because an economy is thus made possible, but also because a source of appreciable energy loss is thus avoided and no arrangement need be made in the station to get rid of the heat developed in such rheostats. The exciter field rheostat, which suffices for each generating unit, can conveniently be fitted into the back of the generator panel.

Each exciter is designed for a 25 kW load at 110 V and is sufficient to supply, without overheating, the excitation of one generator running on a 25% overload, that is to say, 3750 kVA, p. f. 0·75.

The armature of the exciter is carried on the end of the alternator shaft, so that no exciter bearings are required.

As explained further on, under the heading "Auxiliary service", the station is provided with converter sets, the dynamos of which are each designed so as to replace, if necessary, one of the built-on exciters. Under normal conditions these converting sets are used for the auxiliary services of the station only and for battery charging. It is highly important, for the sake of smooth operation of the plant, that it should be possible to switch over simply and quickly from excitation by a direct-coupled exciter to excitation by the dynamo of one of the auxiliary sets, if the former becomes damaged. If one of the converter sets is always kept running either light or under load, direct current for excitation will always be available. To avoid complicated switching operations each alternator has a double set of excitation terminals. The first set is connected to the built-on exciter, and the second is connected by a cable to the reserve dynamo of the converter set. All that is necessary for changing over from excitation by built-on exciter to excitation by the reserve dynamo is to throw over the small two-way switch placed between the two sets of terminals (this can be done without interruption of service and without danger of a wrong switching operation), and then to connect the dynamo to the cable feeding the excitation circuit of the alternator by throwing over a second switch, mounted on the operating panel.

The dynamo has two shunt rheostats placed in series and fitted, one in the station service panel, the other in the panel of one of the main generators. The latter rheostat is used to regulate the alter-

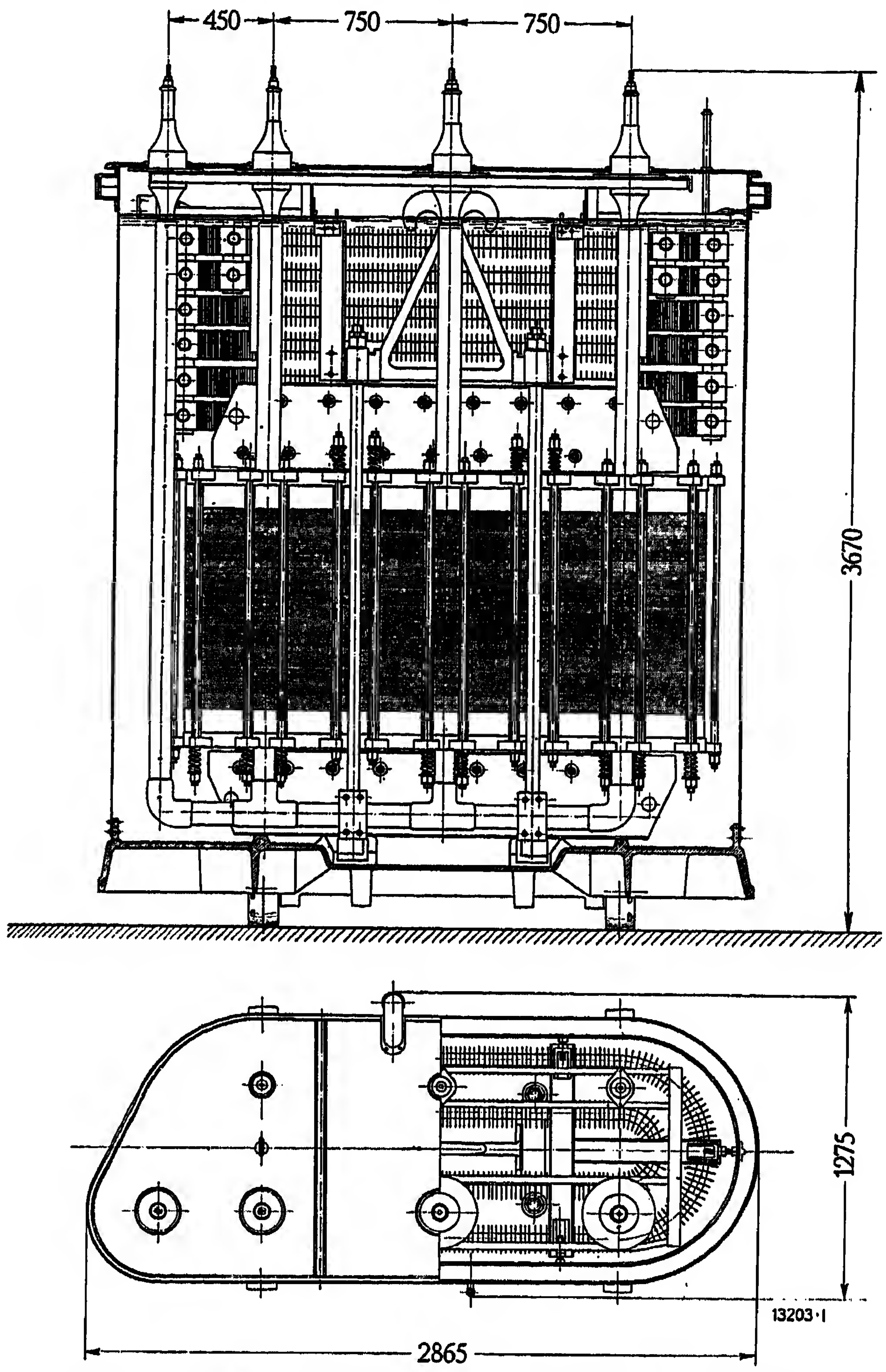


Fig. 5. — Three-phase oil-immersed transformer 3000 kVA, 5000/52000 V, 50 cycles.
Star/star connections with neutral point on the 52000 V side brought out, inside water cooling and patented method of supporting windings.

nator tension, when the reserve set is being used for excitation purposes, so that the attendant is not obliged to leave the main generator panel; he simply regulates by means of another handwheel on the same operating board.

The dynamo of the converter set is provided with regulation poles so that regulation of the alternator tension can be carried out by the field rheostat of the dynamo alone without using a main field rheostat.

It is to be noted that, to simplify the erection and dismantling of the generator sets, the end of the alternator shaft has a tapped hole so that a hook, capable of carrying the whole weight of the rotating parts can be screwed into it. The travelling

crane can thus handle the rotating parts of each set. To allow of inspecting and dismantling the footstep bearing the rotating parts can be raised 40—50 mm and supported on beams placed across the base frame. In this way sufficient clearance is provided above the bearing to allow inspection, etc.

TRANSFORMERS.

To each generator corresponds a transformer of equal output, so that the generator and transformer form a single unit from the electrical point of view. This simplifies the switchgear considerably.

The two transformers installed at present are each built for the following conditions: —

Normal output: 3000 kVA.
Tension ratio: 5000/52 000 V.
Frequency: 50 cycles.
Connections: star/star with neutral point brought out on the 52 000 V side.
Type: Oil-immersed, with water cooling by means of a coil of water piping placed inside the transformer tank.

The transformers are built with a patented device for holding the windings so that they cannot be deformed as a result of the mechanical stress due to short-circuit. This device will be explained further on.

The transformers are built to meet the following guarantees: —

Temperature rise (measured by thermometer in the upper layer of oil): 45° C after continuous full load operation at 3000 kVA. Margin 5° C.
Efficiencies: at full load: abt. 98·46 % with unity power factor.

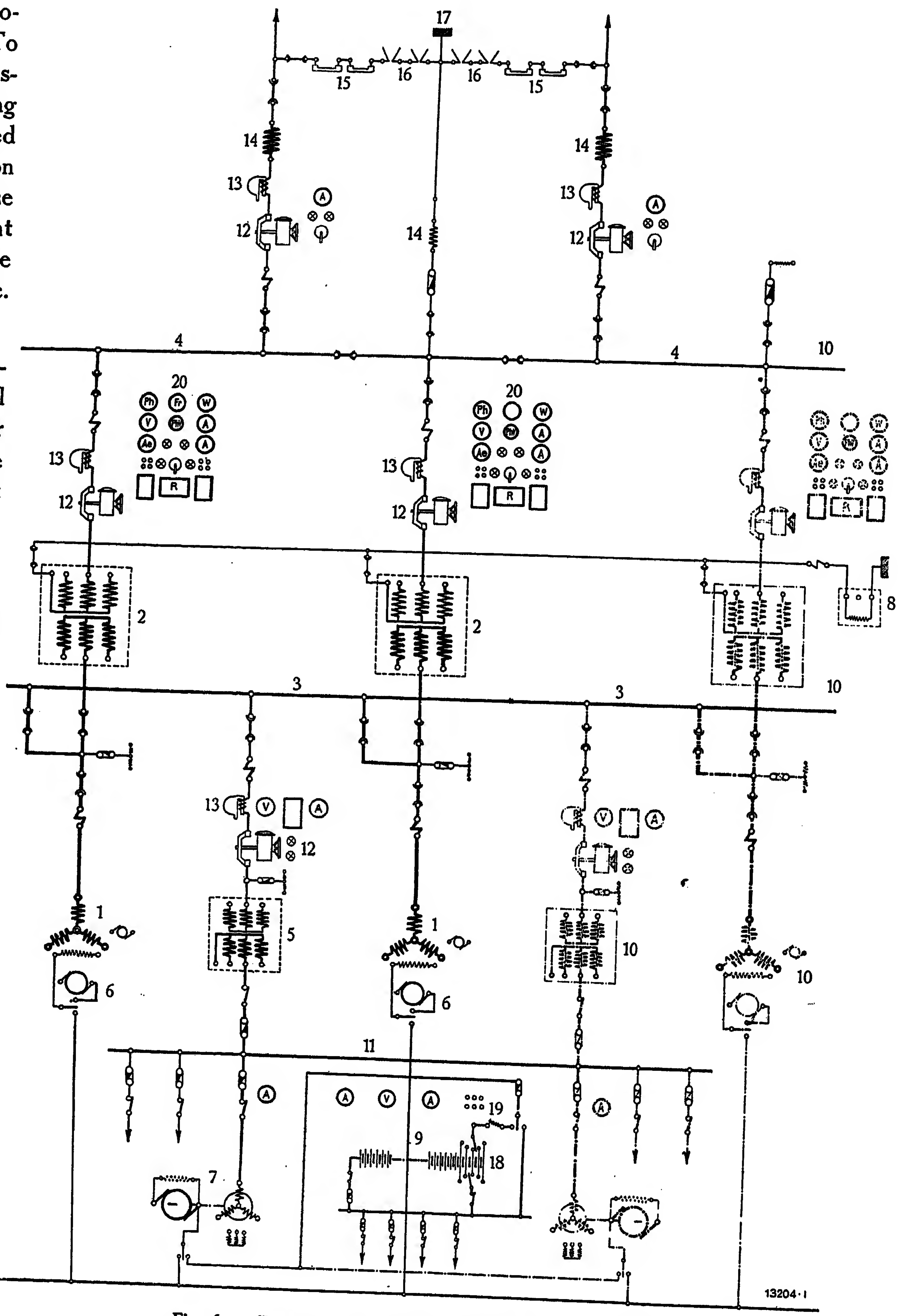


Fig. 6. — Diagram of connections (showing one phase only).

1 = 2 vertical three-phase generators, 3000 kVA, 5000 V, 50 cycles.
2 = 2 three-phase transformers, 3000 kVA, 5000/52000 V, 50 cycles.
3 = 5000 V bus-bar.
4 = 52000 V bus-bar.
5 = Transformer for auxiliary services, 50 kVA, $\frac{5000}{220/115}$ V.
6 = Exciter, 25 kW, 110 V.
7 = Converter set.
8 = Dissonance extinguishing coil.
9 = Battery.
10 = Provision for future extensions.
11 = 220 V bus-bar for auxiliaries.
12 = Oil switch.
13 = Primary current time relay.
14 = Choking coil.
15 = Liquid resistance.
16 = Horn gap lightning arrester.
17 = Earth connection.
18 = Two cell switch.
19 = Minimum current automatic switch.
20 = Measurement and service apparatus.
A = Ammeter.
Ae = Exciter Ammeter.
V = Voltmeter.
Phv = Synchronising voltmeter.
W = Wattmeter.
Fr = Frequency meter.
R = Recording wattmeter.

at full load: about 97·93 % with 0·8 power factor.
Margin: ± 0·4 %.

No load losses: 21 100 W. Margin: 20 %.
Tension drop from no load to full load:

0·85 % at unity power factor,
2·5 % „ 0·8 „ „

Margin: 10 % of guaranteed figures.
Quantity of cooling water required: 42 ℓ per min and per transformer, the temperature of the cooling water at the inlet being not more than 15 ° C.

The design of the transformer is shown in Fig. 7 and the principal features are the following: —

General particulars. The three main transformer columns are all in one plane and supported between two yokes of trapezoidal shape. The active core is rigidly held in position and compressed by pressure pieces, above and below, connected by bolts which are liberally dimensioned so as to reduce to a minimum the humming of the transformer when on load. If the pressure bolts are removed and the upper yoke lifted off, the windings are exposed, either for removal or for changing connections if necessary.

The upper holding-down piece carries a lifting device with hook which allows of raising the active core along with the windings out of the tank by means of the travelling crane.

Windings. These are what are termed double concentric windings, that is to say, the high tension winding on each column is placed between two sleeves formed of low tension winding. The low tension winding is itself subdivided into a large number of sections and carefully insulated from the high tension coils.

The coils placed nearest to the transformer terminals are provided with special insulation as an additional precaution against the effects of surges.

Both high and low tension windings are tightly compressed between two cast steel pressure rings, the pressure being produced and maintained constant by heavy spiral springs. This device is a real and efficient

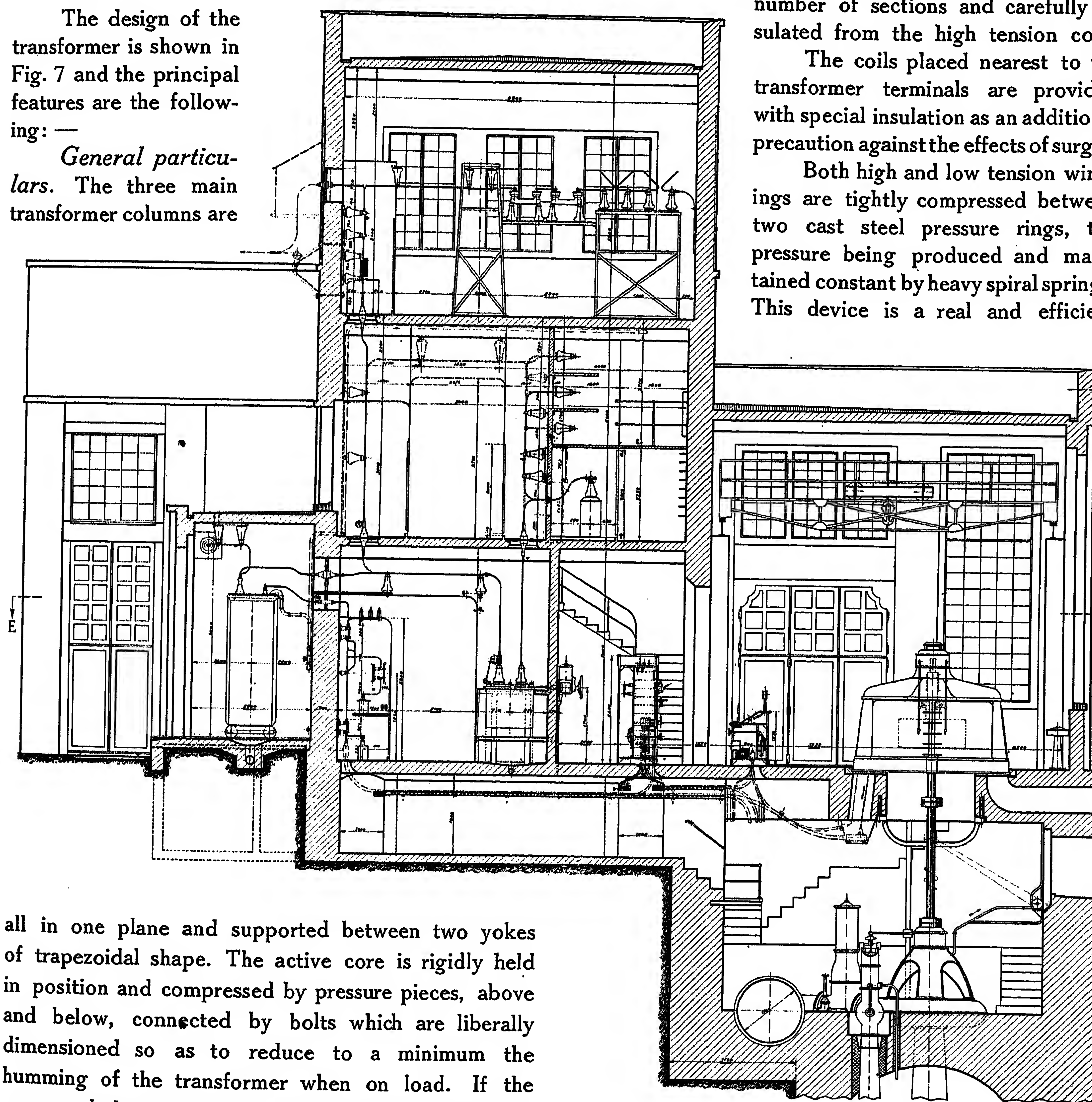


Fig. 7. — Transverse section of the switch house.

safeguard against the effects of short-circuits, and Brown, Boveri & Co. have used it for years with the best results.

In the event of a short-circuit, the circular form of the coils makes radial deformation impossible. Axially, however, the springs mentioned above give a little, thus allowing a slight displacement of the coils under the mechanical stress produced by the short-circuit. In this way the coils are saved from permanent deformation. Whenever the short-circuit has passed, the springs reassert their influence and bring the windings back to their original position. Numerous tests specially carried out with transformers provided with this device have shown that they will stand up to short-circuits of the severest kind without deterioration.

Tank. This is built of thick smooth boiler plating mounted on a cast iron base. The latter is made with stout lifting trunions to allow of raising the complete transformer filled with oil by means of chains or stout ropes. The cover of the transformer can be removed without dismantling the terminals. The active iron and windings can be lifted out of the tank together with the cooling water piping without touching the electrical connections, after first unbolting the pipe flanges and loosening the distance bolts which hold the active core in position within the tank.

Cooling device. Cooling is effected by a current of cold water passing through a coil of piping placed in the upper part of the tank above the transformer proper. This arrangement produces a good circulation

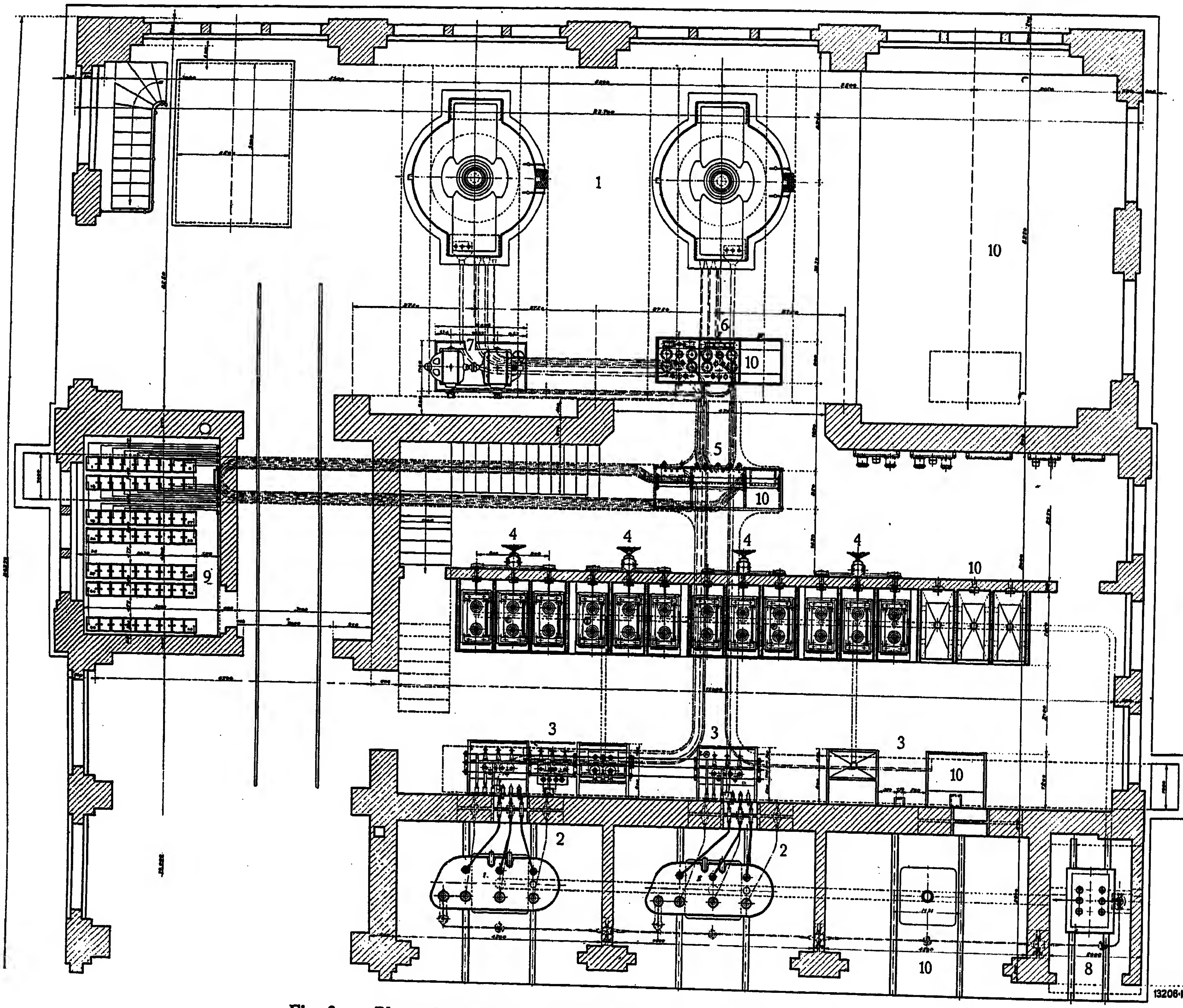


Fig. 8. — Plan of the switch house (ground floor), section E F, Fig. 7.

1 = 2 vertical three-phase generators, 3000 kVA, 5000 V, 50 cycles.
2 = 2 three-phase transformers, 3000 kVA, 5000/52000 V, 50 cycles.
3 = Switch cells for 5000 V side.
4 = Switch cells for 52000 V side.
5 = Operating switchboard for auxiliary services.
6 = Switch desk for generators.
7 = Converter sets.
8 = Dissonance extinguishing coil.
9 = Battery.
10 = Provision for future extensions.

of oil in the tank so that no part of the windings reaches a dangerous temperature through inefficient circulation.

The cooling coil is composed of a spiral of galvanised iron tubing with ribs placed at short in-

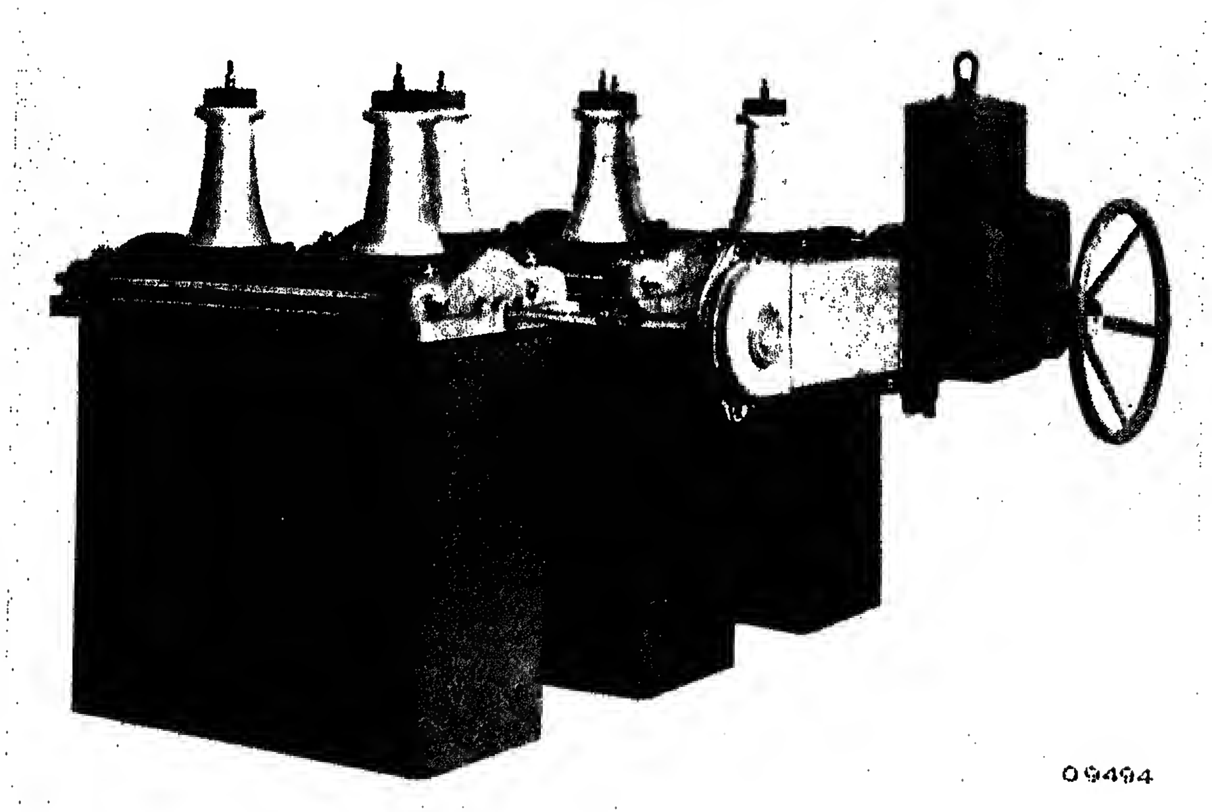


Fig. 9. — Oil switch for 52000 V with electro-magnetic distant control.

tervals along its length increase the surface. It is tested under a pressure of 10 at although the actual pressure of the water is never greater than 0·5—1 at. The various turns of the coil are separated by distance pieces and the complete spiral is contained in a light frame of angle iron which rests on the upper yoke of the transformer. On the top of this frame is fixed the bar that carries the leading-through insulators for the transformer terminals.

If the cover of the transformer is removed, the terminals dismantled, the connecting flanges of the inlet and outlet water pipes unbolted and the bolts holding the spiral to the frame removed, the spiral can be lifted bodily out of the tank without difficulty.

Various features. The transformer proper is carefully distanced from the inside walls of the tank so as to make erection easy and to allow of raising the active core when necessary.

The tank is provided with an oil cock for emptying purposes and with an oil gauge. The cover is built with an aperture to allow of adding oil when necessary, and in which the thermometer indicating the temperature of the oil is inserted. Any break in the flow of cooling water is immediately notified by an automatic device placed in the water supply pipe and operating an alarm bell.

The base plate is provided with rollers to allow of moving the transformer, these rollers having holes in which levers can be placed.

The oil having been delivered separately the transformers, after filling, were dried out on site before being put to work, according to the usual practice.

Each unit with tank but without oil filling weighs abt. 13 500 kg. About 5000 kg of oil are necessary per unit.

The neutral point of the high tension winding is brought out for the purpose of connection to a dissonance extinguishing coil of Brown Boveri type which was put into the station at the end of 1921, and the working of which will be explained when the switchgear is discussed. For this reason the tank is not symmetrical in shape, the design being chosen so as to reduce to a minimum the quantity of oil necessary for filling the tank.

AUXILIARY STATION SERVICE.

For supplying the needs of the station itself low tension three-phase A. C. and D. C. are used.

The three-phase A. C. supply is used for light and power, that is to say, it supplies the lighting of the station proper and surroundings, and also power for the motors of the water gates and repair shops, etc. This current is supplied by a three-phase transformer fed from the auxiliary 5000 V bus-bars and built for 50 kVA and 220/115 V on the low tension side. This transformer is of the oil-immersed type with natural cooling by surrounding air. The tank is of corrugated metal sheeting and rests on a cast iron base to which it is welded so that no loss of oil need be

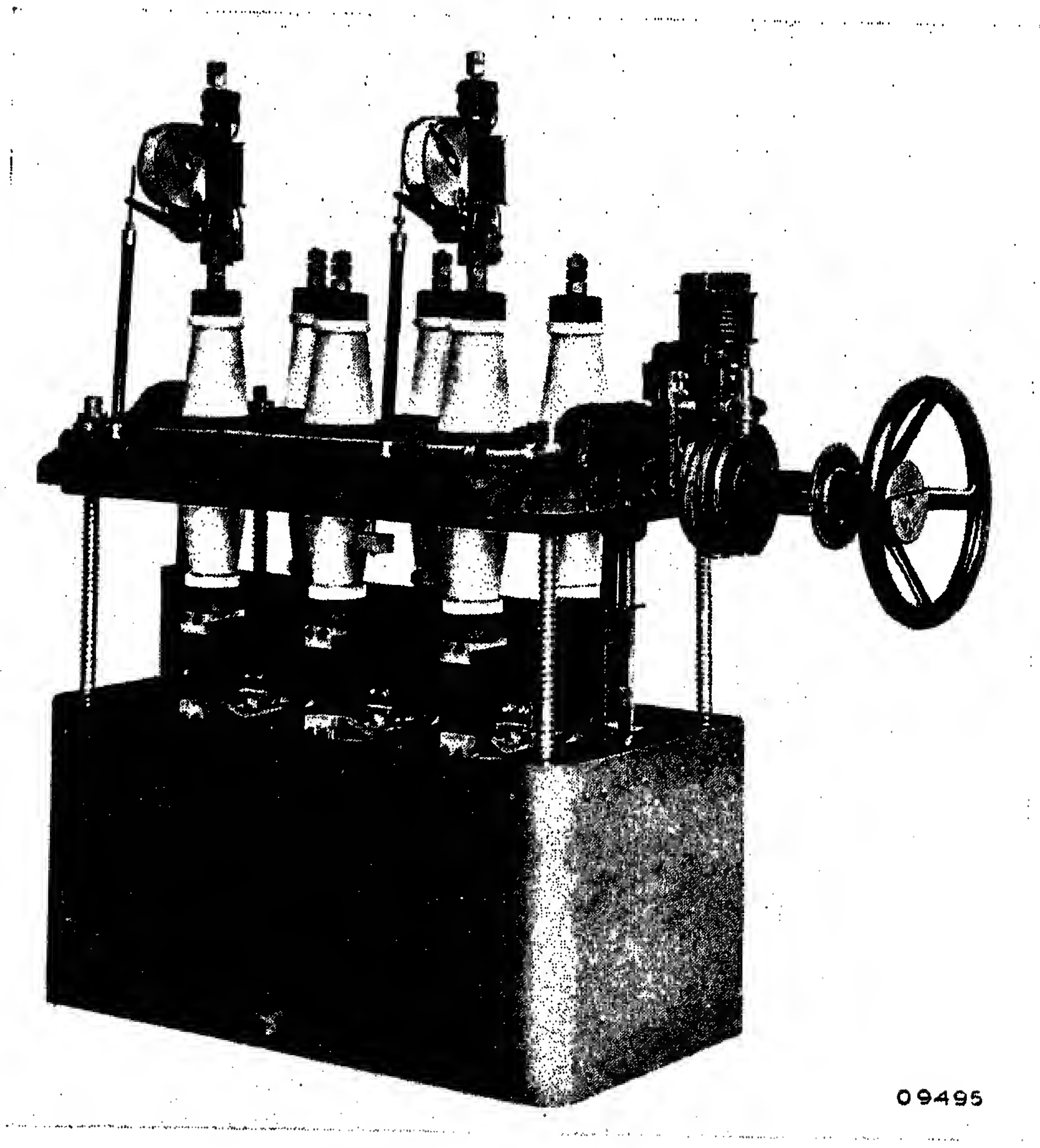


Fig. 10. — Oil switch for 5000 V.

feared. The base is provided with rollers and the tank with an oil cock. The cover is of heavy plating reinforced by angle iron and provided with eye bolts by means of which the whole transformer can be lifted. Apart from the terminals, this cover possesses two apertures, one for ascertaining the oil level, and the other for inserting the thermometer to measure the temperature of the oil.

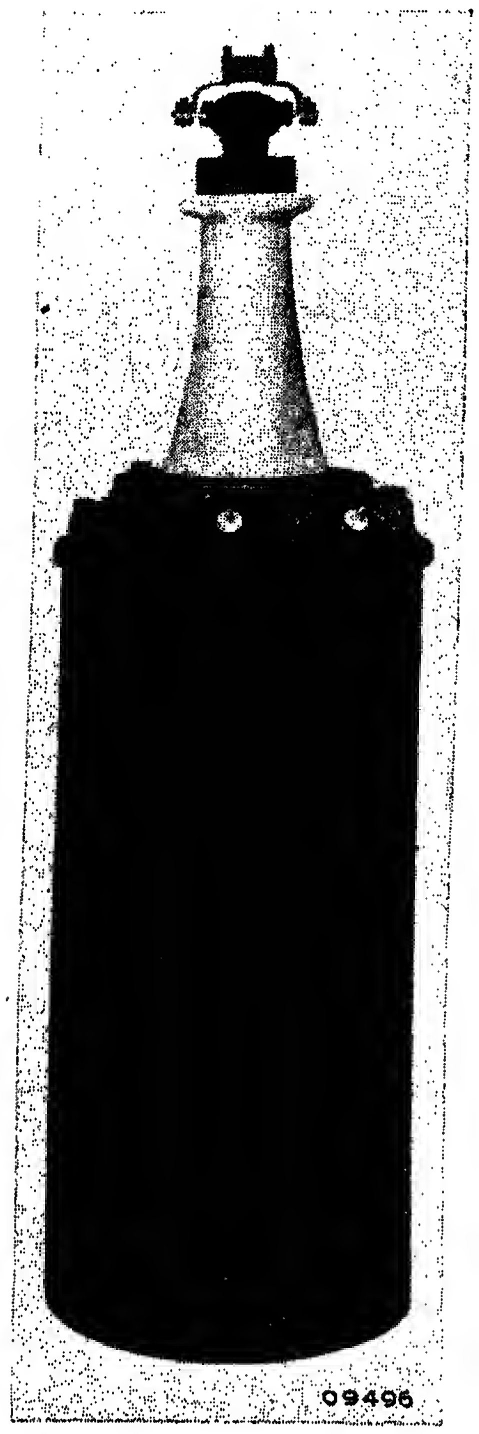


Fig. 11. — Current transformer for 52 000 V with built-on protective resistance.

The D. C. supply is used for the remote control of the oil switches, also for signal lamps, control lamps, small motors for regulating within certain limits the speed of the turbines by influencing the turbine regulator and which are mounted on the latter and, lastly, as a reserve source for lighting if the A. C. supply fails. If, as was explained before, one of the built-on exciters of the main generators is damaged, direct current from the auxiliary supply is used.

There is one converter set and one battery in the station as sources of direct current supply. The converter set comprises a three-phase slip-ring induction motor of 29 kW 220 V, 1450 r.p.m. direct coupled to a 26 kW dynamo, the tension of which can be regulated between 110 and 160 V, this range being necessary for battery charging. The two machines have a common bedplate. The output of the dynamo was chosen so that it would suffice for exciting one main generator if required.

The battery contains 63 Tudor cells type J6 and has a capacity of 216 Ah with a discharge rate of 10 h at about 22 A. The maximum discharge current is 54 A during 3 h, which corresponds to 162 Ah.

Room has been left for a second station transformer of 50 kVA and for a second converter set. This plant will, however, only be installed when the station has been enlarged.

DISTRIBUTION AND SWITCHGEAR.

The complete equipment of the station will comprise three hydro-electric generating sets, of which two have been put in to meet the needs of the first period of service.

The diagram of connections is of the simplest, because there is only one set of main bus-bars which are placed on the 52 000 V side and to which the main transformers are connected as are also the outgoing lines. Each generator feeds these bus-bars through the transformer to which it is directly connected, there being no oil switch on the 5000 V side between alternator and transformer.

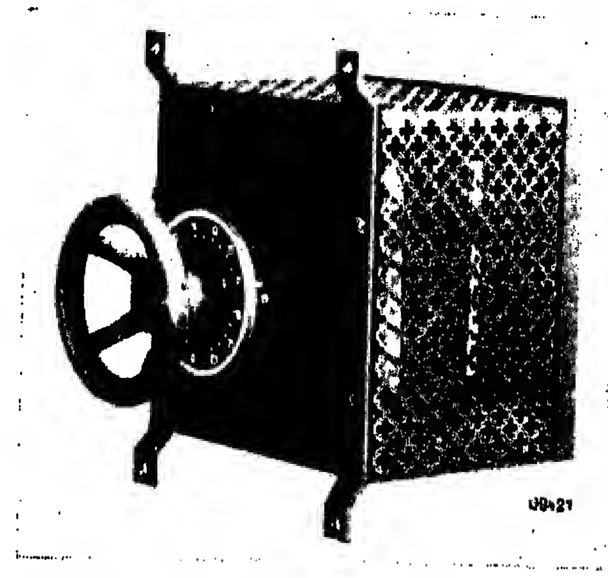


Fig. 12. — Shunt field rheostat for the exciter.

There is, however, a set of auxiliary bus-bars on the 5000 V side which allow of feeding the station transformer by any one of the generators. The generators can be connected to the auxiliary bus-bars by means of hinged knife disconnectors provided with an interlocking device which excludes the possibility of wrong switching.

The auxiliary bus-bars can also be used for connecting a generator to a transformer belonging to another set. If, for example, the generator of one set is in repair and the transformer of the second set as well, then generator (2) feeds the transformer belonging to generator (1). This is, of course, not a very probable state of things.

Each main transformer has an oil switch placed on the 52 000 V side between it and the bus-bars. The fact of there being no other oil switches and only one set of main bus-bars not only simplifies the layout of the switchgear but is a guarantee of reliability, as, the fewer pieces of apparatus used the less likelihood there is of breakdowns.

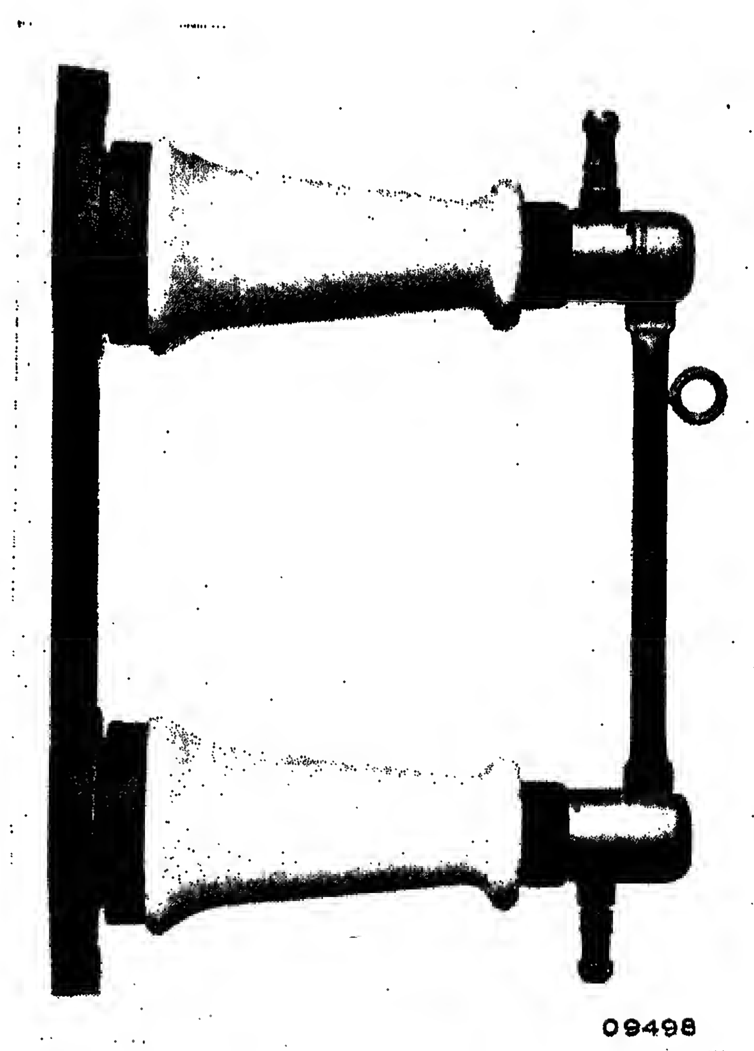


Fig. 13. — Disconnecting switches for 52 000 V.

Two outgoing air lines take off from the 52 000 V bars, each being provided with an oil switch and the usual measuring instruments, etc.

As the Buitreras power station is built to work in parallel with the older station of Cor-

chado it was necessary to provide the Buitreras bus-bars with a pressure transformer which is always under tension and which is used for synchronising the two plants. It is an easy matter in case of a breakdown in either of the two stations or on one of the lines to reorganise the distribution of power and to connect or separate the two power houses according to circumstances.

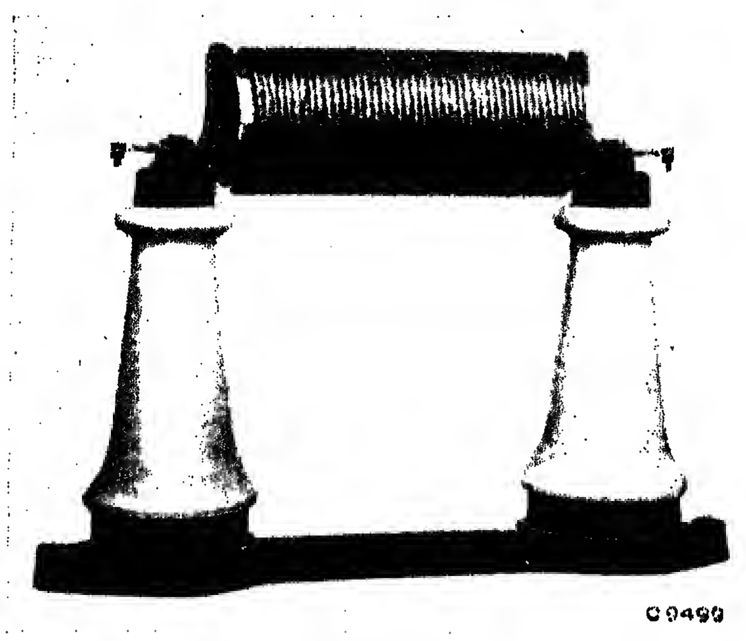


Fig. 14. — Dissonance extinguishing coil for 52 000 V.

Protection against static charges is provided for by a set of oil-immersed earthing coils with iron cores connected to the 52 000 V bus-bars. Further each of the two outgoing lines has a set of horn gap lightning arresters in series with liquid resistances.

Finally, as mentioned before, the neutral point of the 52 000 V side of each transformer has been brought out to a terminal on the transformer cover, and all these terminals are connected to one end of an extinguishing dissonance coil of Brown Boveri type the other end of which is grounded. This was added to the station at the end of 1921. To explain the effect of dissonance coils it will be sufficient to say here that by earthing the neutral point through an inductive resistance such as one of these coils a very efficient protection against the results of earths is obtained, because the lagging inductive current which passes through the coil as soon as an earth takes place somewhere on the line practically neutralizes the leading capacity current flowing to earth and in this way the amplitude of the surges produced on the system by the earth is reduced to admissible limits. Further the extinguishing dissonance coil improves the distribution of load between the three phases and reduces the asymmetry of the phase currents in case of an earth.

All the oil switches on the 52 000 V side are provided with built-on overload time limit relays in the main circuit. These Brown, Boveri built-on relays can be accurately set to trip the switch with a given current and in a given time, and the time and current settings can be done independently of one another by simply moving two pointers on the relay. These relays are characterised by the feature that the time required to trip the switch is independent of the strength of the current which causes the relay to operate. For this reason they are often termed primary independent relays.

It is only in the case of a big overload amounting to about three times the usual current that the opening of the switch is instantaneous. This is attained by the use of a special spring which reinforces the effect of the other springs in the event of a short-circuit. This short-circuit spring can, however, easily be put out of action if desired. These new relays embody the very latest improvements made by Brown, Boveri & Co. in this type of apparatus; made as they are with careful workmanship in every detail they fulfil all the varied conditions required by every kind of power distribution service.

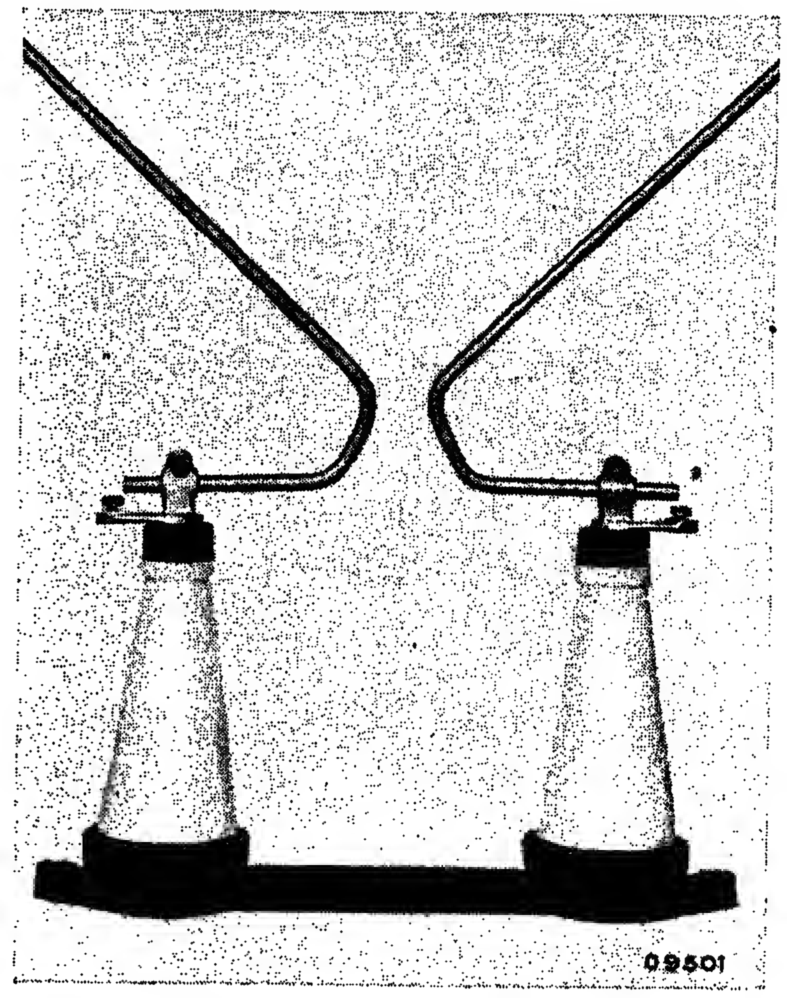


Fig. 15. — Horn gap lightning arresters for 52 000 V.

Layout. The general layout of the station is shown on the following drawings: Fig. 9, Plan of ground floor, Fig. 8, Longitudinal section.

The arrangement of the switch house will be made clear by the following remarks: —

The switchgear building is placed at the back of the machine room and extends along the whole length of the latter. The ground floor is built to take the cells holding the transformers, but as seen on the drawings these cells are shut off by a partition from the rest of the switch house. Generally speaking, machine room and switch house form a compact building of pleasing appearance. The latter has two stories, the ground floor being on a level with the floor of the machine room. It was decided at first to raise the ground floor of the switch house above the level of the machine room, but this idea was given up principally because the latter is of moderate dimensions and it seemed better to have the two floors on the same level as it was found possible to place the panels so that the view of the machine room obtained from the operating board is quite comprehensive without raising it, that is, without placing either desk panels or vertical panels on a raised

stage or gallery, as is often done. The operating desks of the three alternators are placed in front of the middle alternator.

The current generated by the alternators is carried by armoured cables from the generator terminals to the cells of the auxiliary 5000 V bus-bars, the cables being placed in trenches. These cells hold the disconnecting switches for the 5000 V bars and the measuring transformers. From here the current is led to the main transformers by bare copper connections which are carried in leading-through insulators through the partition isolating the switch house from the cells holding the transformers. As explained above, the two parts of the building (transformer cells and the rest of the switch house ground floor) are thus completely separated one from the other and it is possible to remove or put the transformers back in their cells from outside without going through the machine room or the switchgear house. This is an excellent solution for simplifying service and makes for greater safety.

Each transformer in its own cell is shut from without by means of a corrugated iron roller screen. This screen is in reality the door of the cell which is raised for putting in or removing the transformer. Each transformer cell is provided with an oil outlet duct, the object of which is to collect any oil that may spill over from the tank in case of explosion or fire. This oil duct ends in a concrete well where the oil is collected to be then extracted, refiltered and used again. The transformer cell is also designed for taking the pipes leading cooling water to and from the transformer tank. This water comes from a reservoir on the first storey of the switch house.

After passing through the main transformers the current is led by conductors in leading-through insulators for the second time through the wall of the transformer cell to the 52000 V switches. These are also on the ground floor and at the back of the operating and service board. The 52 000 V switch cells are face to face with the 5000 V cells and are separated from the latter by a corridor which is wide enough to give passage to a truck running on a set of rails and used for removing the oil switches. The 52000 V switch cells are built with expansion lids and a pipe for carrying off oil. These cells are completely isolated from the machine room by a partition which is pierced only by the end of the switch spindles to which are coupled the remote control devices for operating the switches, the latter being only accessible from the operating board.

The first storey of the switch house contains the main 52 000 V bus-bars and the cells with the 52 000 V measuring instruments and disconnecting switches.

The second storey contains the lightning arresters, accessories and outgoing line gear. The drawings give all details so clearly that further description is scarcely necessary.

In a general way it may be said that the layout incorporates in every detail the very latest improvements in power house design and that it combines facility of service and with maximum security.

In particular, attention is drawn to the fact that switches, transformers, operating switchboards, in short all parts of the plant requiring a certain supervision, are placed on the same floor (the ground floor). This is a feature much appreciated by the station staff.

Further, the whole arrangement of the switchgear has gained in simplicity by this feature — an advantage to be reckoned with, as it makes for easier service conditions and greater security.

F. R. (C. M.)

THE INFLUENCE OF LOW TEMPERATURES ON MINERAL OILS IN TRANSFORMERS AND OIL SWITCHES; TESTING OF OILS AT LOW TEMPERATURES.

Decimal index 620. 19 : 665. 4.

FOR transformers and switches mineral oils are now almost exclusively employed. These, like all liquids, solidify at low temperatures. The solidification of oil does not take place at a precise well-defined temperature as in the case of water, but is a continuous thickening process. This behaviour is due to the fact that mineral oils are not simple chemically-defined liquids, but a mixture of many different hydro-carbons whose freezing points are widely separated. With a decreasing temperature certain components separate and solidify, especially the paraffin and bitumen particles. These form a network which diminishes the fluidity of the oil. With oil which has set it is necessary to exert a certain minimum pressure in order to produce a flow and overcome the internal rigidity due to this network. Oil in this state loses the characteristic property of a true liquid where the rate of flow is proportional to the applied pressure provided the critical speed is not exceeded — otherwise an eddying motion would set in.

The thickening of oils in transformers and switches has certain disadvantages and dangers, of which the following paragraphs give a general survey.

A. In transformers. If the oil loses its fluidity on account of a considerable drop of temperature the circulation of the oil is stopped, and heat transmission by convection no longer takes place. Temporary local overheating in the parts where heat is developed is then possible in spite of a low overall temperature. An idea of this danger can be got from a simple experiment. Fig. 1 shows the variations in temperature of the wire resistance of a heater element immersed in a transformer tank containing oil at —11° C. The oil had a consistency like grease, as it lost its fluidity at 4° C.

The current was adjusted so that the permanent temperature of the wire was about 60° C above that of the surrounding air. Fig. 1 shows that during this test the temperature of the wire first rose and attained a maximum value (77° C) which lasted five minutes; after that it dropped again rapidly for a time and then gradually assumed a steady value. If a similar experiment be made in air at a temperature of 40° C — the maximum surrounding temperature allowed for in France by the Chambre syndicale des constructeurs de gros matériel électrique — the load remaining unaltered, then the final working temperature of the resistance would be about 95° C, which is permitted by the British standardisation rules for electric machines. The maximum temperature reached in the tank filled with oil which had set was therefore well below the maximum allowable working temperature.

In transformers the danger of overheating is appreciably less as the surface and heat capacity of the body giving out heat are much greater than in the preceeding experiment; the danger of overheating is therefore not to be feared as long as the temperature at which the oil solidifies is well above 4° C.*

Transformers with an oil circulating system are more liable to perturbations.

The resistance due to the oil which has set in the piping is often great enough to check the circulation. The pressure produced by the oil pump is not sufficient to make the oil move and the cooling of the transformer is completely interrupted.

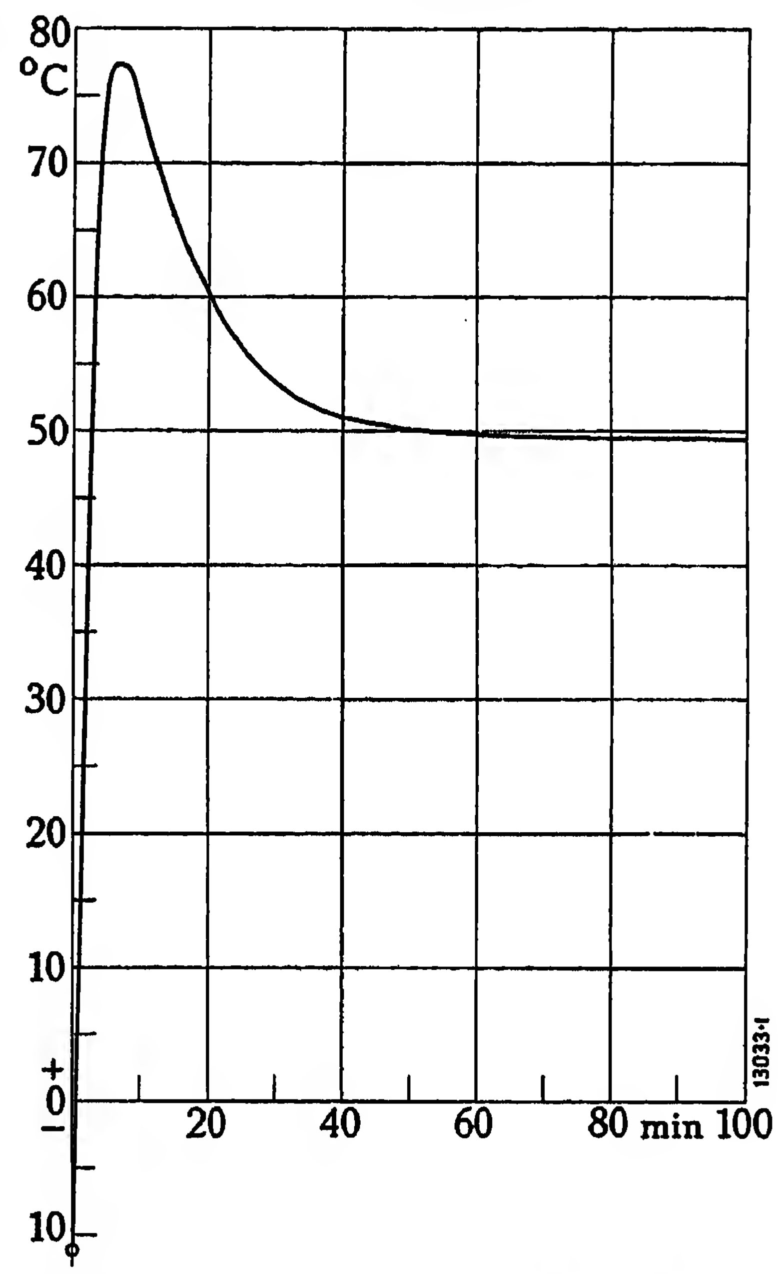


Fig. 1. — Variation of temperature of a resistance wire in set oil at —11° C.

The low temperatures mentioned are only likely to occur with transformers placed out-of-doors or in unheated buildings; for instance, transformers on posts, locomotive transformers with external cooling coils, etc. Even in these cases the oil only sets when the transformer is out of use for some time, as the no load losses suffice otherwise to keep the oil liquid. With water-cooling of the oil a small constant flow of water is sufficient to prevent the oil from setting and the water from freezing in the cooling coils.

* There is also no danger of overheating with oil-immersed starters.

B. In oil switches. The setting of the oil is much more serious in this case, especially with switches having to break the circuit on overloads (short-circuits for instance). In all cases where the oil might set there is a danger of the operation of the plant being interfered with and the latter being damaged. The thick consistency of the oil makes the extinction of the arc difficult, so that with heavy loads the switch is liable to be destroyed through the oil catching fire or an explosion.

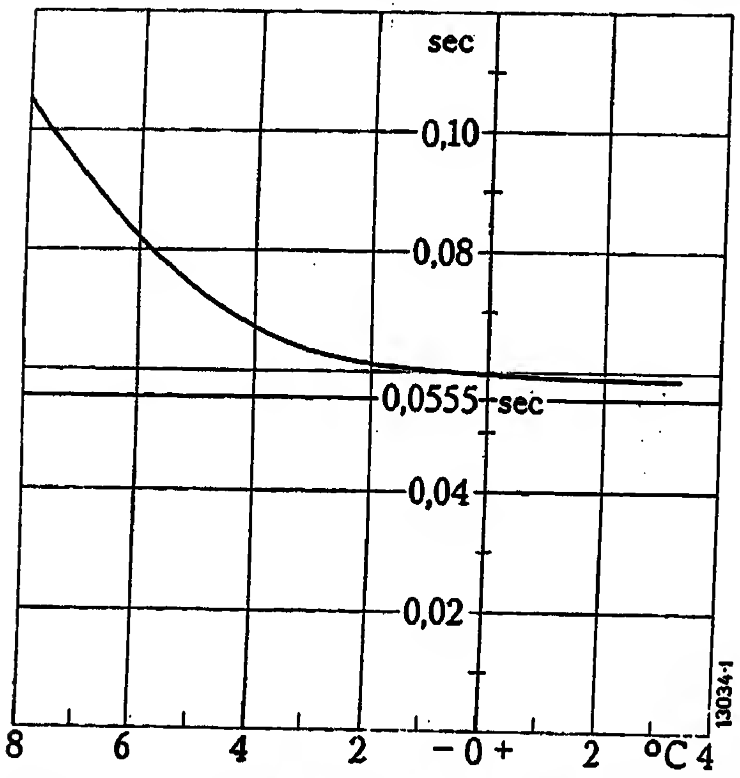


Fig. 2. — Time to break circuit with switch A6/3 filled with oil which sets at —3° C.
The horizontal line (0·055 sec.) represents the breaking time in air.

The breaking of the circuit is hindered by thick oil for two reasons: —

(1) The movement of the contact bar is delayed, which causes the arc to persist longer; and

(2) The oil, on account of its thickness, does not immediately fill the space between the contacts.

Various tests undertaken to determine the influence of these two factors have given the results plotted in Fig. 2, which shows the time taken to break the circuit by a standard A 6/3 switch, as a function of the temperature, oil setting at approximately —3° C being used. At — 8° C for instance, the oil was so thick that its surface remained uneven if disturbed; at this temperature the time taken was 80 % longer than with very liquid oil.

The length of the arc gives an indication of the effect of the sluggishness of the oil. This, as well as the duration of the arc in a small oil-switch of an old type built for an inductive load of 700 kVA, 1400 V, is given in Fig. 3. The curves have been plotted for a switch with one breaking point, and also with five breaking points in series. For these tests the switch was filled with an oil which was quite thick even at ordinary air temperature (cylinder oil with a viscosity — measured in Engler's degrees* — of 100 at 40° C and 720 at 17° C).

The influence of the second factor is shown clearly by the increase in the *length* of the arc at low temperatures. (If the fluidity of the oil remained unchanged the length of the arc would diminish slightly with the reduced speed of breaking.) Therefore in reality these two factors together affect the values obtained giving the *duration* of the arc. The amount of gas produced on breaking the circuit is given in Fig. 4. This also serves to show the deleterious effect of the thickening of the oil. The conditions are the same as in the preceding experiments and there is one breaking point. In order to prevent the flame reaching the surface it is necessary to have a certain minimum height of oil above the contacts. With cylinder oil at 38° C this height was found to be 30 % greater than with ordinary switch oil. The duration of the arc, as well as the production of gas with oil of 720 Engler's degrees, was about double that with an ordinary liquid oil.

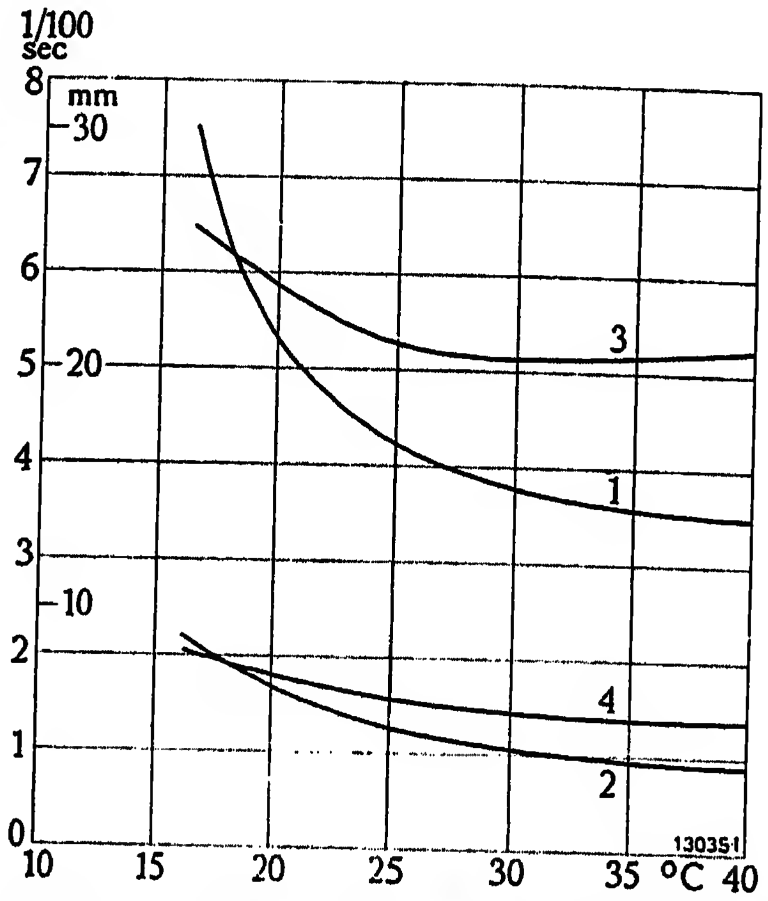


Fig. 3. — Duration and length of arc in a switch with cylinder oil.
1. duration of arc with single break
2. " " " " five breaks
3. length " " " single break
4. " " " " five breaks.

The foregoing results, which were obtained with a switch of comparatively low power would probably not undergo any radical changes, even if switches of much higher power were used. With oil that has set one may therefore expect unfavourable results.

TESTING OF OIL AT LOW TEMPERATURE.

It is necessary to examine the behaviour of oil when it is cooled, on account of the danger of disturbances in transformers and switches due to its thickening. Several methods of examination exist but all possess certain shortcomings; they will be considered here in detail. A new method has been deduced from these older ones and will be described further on.

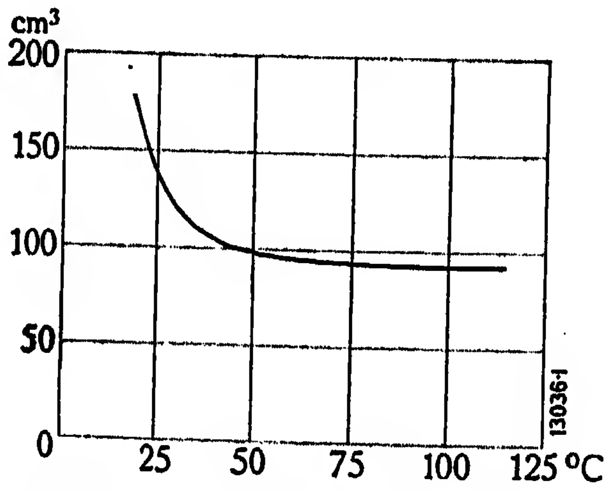


Fig. 4. — Volume of gas produced on tripping a switch filled with cylinder oil.

The simplest method is to examine the behaviour of the oil in a test-tube and note its consistency (like syrup, vaseline, wax, tallow, etc.).

* Engler's degrees, which are measured by Engler's viscosimeter, are determined by the ratio of the rate of flow of a given volume of oil to that of the same volume of distilled water at 20° C. 720 degrees correspond to a flow lasting 15 seconds with the setting point method.

The disadvantages of this method, formerly used by Brown Boveri, are that no numerical values are obtained for characterizing an oil and that the results recorded depend largely on the observer. Further the unavoidable agitation of the oil causes it to remain liquid to a lower temperature. The results are therefore not reliable.

These disadvantages are obviated by the method described by Holde*.

The sample of oil is cooled to the desired temperature in a U-shaped test-tube and an air pressure of 50 mm water gauge applied for one minute. This causes the oil to flow. The height the column rises is a measure of the consistency of the oil at the temperature chosen. This method gives a single definite value at every temperature which serves to characterise the fluidity; however, it does not enable the exact temperature corresponding to the transition from the liquid to the solid state of a given oil to be fixed. There is no simple relation between the rise measured and the viscosity of the oil; this constitutes a drawback to the method. (A single point which would enable the oil to be characterized is much sought for in practice.)

The new method is based on the behaviour of oil when it is cooled. As already stated, the solidification of mineral oils begins by the separating out of solid particles which form a network imparting a certain static rigidity to the oil. At a given temperature oil no longer behaves as a perfect liquid. In an curve showing the viscosity as a function of the temperature this point is characterised by a bend, due to a sudden more rapid increase of viscosity with falling temperature. This caracteristic temperature can be determined with sufficient exactness for practical purposes, as experiments have shown.

The following method has for its object the determination of the bend mentioned. It resembles Holde's method in that a U-shaped test-tube is used. Instead of the rise of level in a given time, the time taken for a given rise is measured. The air pressure used (400 mm w. g.) is comparatively great compared to the rise of oil in the tube. This method gives values which are almost exactly proportional to the absolute viscosity measured in $gr \cdot sec/cm^2$. (The latter must not be confused with the viscosity expressed in Engler's degrees, as these are not proportional to the absolute viscosity.) This naturally holds good only as long as the oil remains liquid. When a substance does not satisfy the laws of flow, the notion of viscosity, in a physical sense, can no longer be employed.

The characteristic point which serves to define an oil has been called by Brown Boveri the "*Setting point*". As already mentioned, it coincides with the bend on the viscosity curve. This designation is considered more suitable than the existing terms: "Freezing point", "Point of solidification", etc.

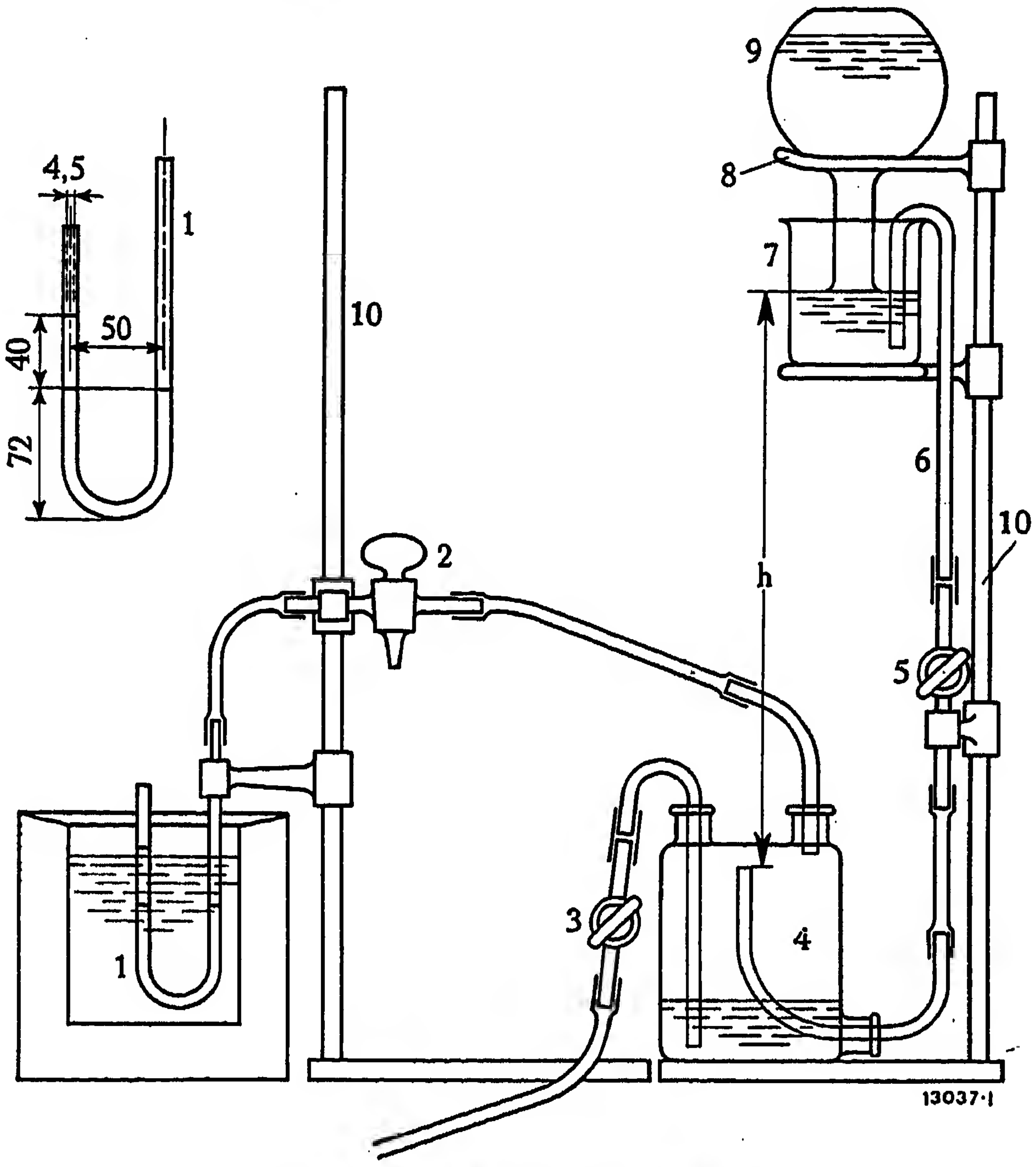


Fig. 5. — Apparatus for determining the setting point of oil.

1 = U-shaped test tube.	6 = Syphon.
2 = Three-way cock.	7 = Glass receptacle.
3 = Drain cock.	8 = Fork.
4 = Woulf's bottle.	9 = Inverted bottle.
5 = Cock.	10 = Bracket.

APPARATUS AND METHOD USED TO DETERMINE THE SETTING POINT OF OIL.

The general arrangement is shown in Fig. 5. (10) is a bracket supporting a glass receptacle (7) containing water. On opening the cock (5) the water tends to flow through the syphon (6), which must always remain full, to the Woulf's bottle (4). A pressure is thereby produced in the latter; it may be measured directly in mm of w. g. by the height h, which is equal to the difference of the water levels. By means of an inverted bottle (9) which rests on a fork (8) the level in (7) is kept constant. The fork (8) allows the bottle (9) to be easily refilled. It is only necessary to turn it upside down quickly and hang it on the fork. The U-shaped glass tube (1) has three graduations as shown in the figure. (2) is a three-way cock which allows

* Holde, "Untersuchung der Kohlenwasserstofföle und -Fette," 4th edition, p. 165.

the test-tube to be put in communication with the atmosphere or with the air under pressure. The drain-cock (3) serves to empty the Woulf's bottle when it becomes full.

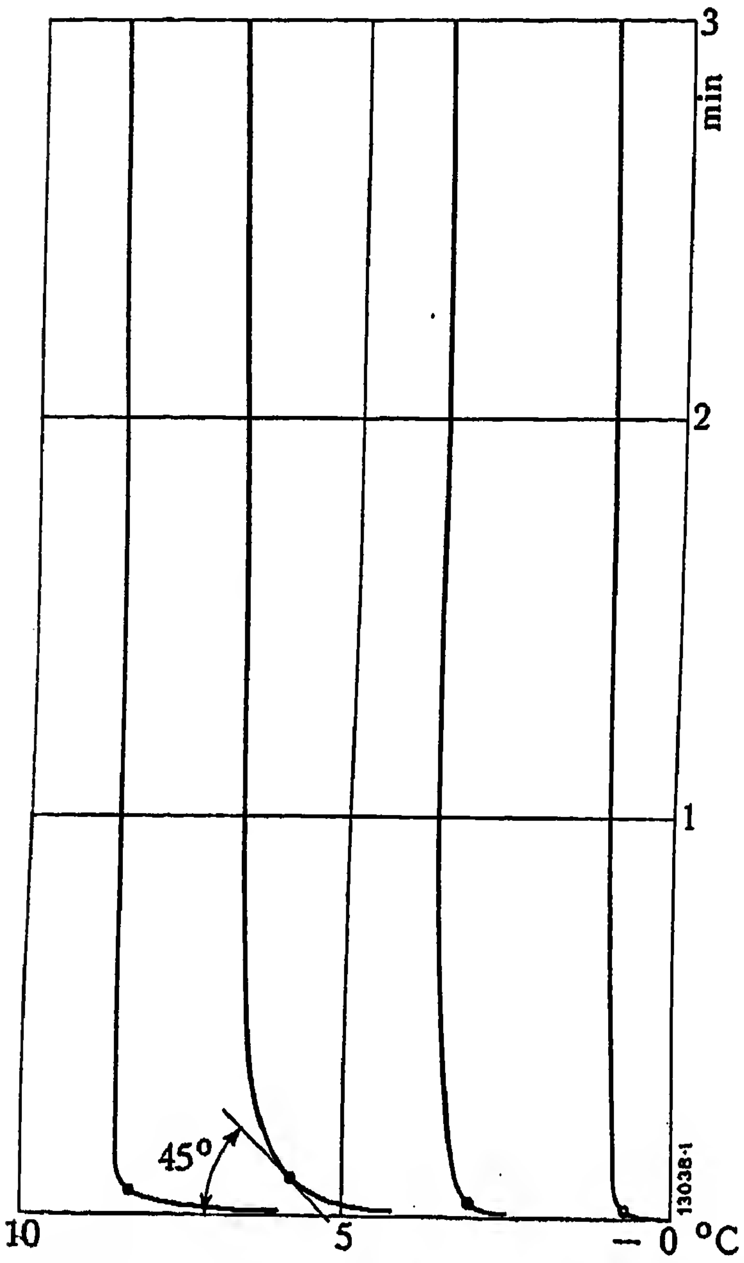


Fig. 6. — Flow curves of transformer and switch oils.
• Indicates the setting point.

The height of the water column h of 400 mm is kept automatically constant. The bore of the U-tube (4·5 mm) must be the same also at the bend. On account of the contraction due to cooling, the test-tube is filled to approximately 1 mm above the lower graduations with the oil to be tested.

The next thing to determine, before undertaking the definite analysis, is the approximate setting point. This is done by simply inclining the test-tube and observing the thickness of the oil. The points on the flow curve must be determined at intervals of a few tenths of a degree. Any desired temperature down to — 21° C can be obtained by using a mixture of finely powdered ice and cooking salt. The test-tube is left about three minutes in the mixture — which has to be stirred — and must not be disturbed, as otherwise the formation of the network would be interfered with. The air under pressure is then applied and the time taken to reach the upper graduation is measured with a stop-watch. Before each measurement the test-tube must be placed in tepid water so that the oil becomes completely liquid again.

When the test-tube is used to examine another oil it must be washed with benzine and then dried. If the Woulf's bottle (4) is full of water it can be emptied by opening the cocks (2) and (3), and closing the cock (5). On inverting the bottle (9) after filling, the water in the glass receptacle (7) may rise too high. It has to be brought back to its normal level by drawing off water at the drain cock (3).

Fig. 6 shows the flow curves, obtained by this method, of some transformer and switch oils. In Fig. 7 the flow curve of a resinous oil is given. On comparing it with the preceding curves it will be noticed that it has no setting point. Even when the flow takes an hour or even longer, tests have shown that it still possesses the characteristics of a liquid.

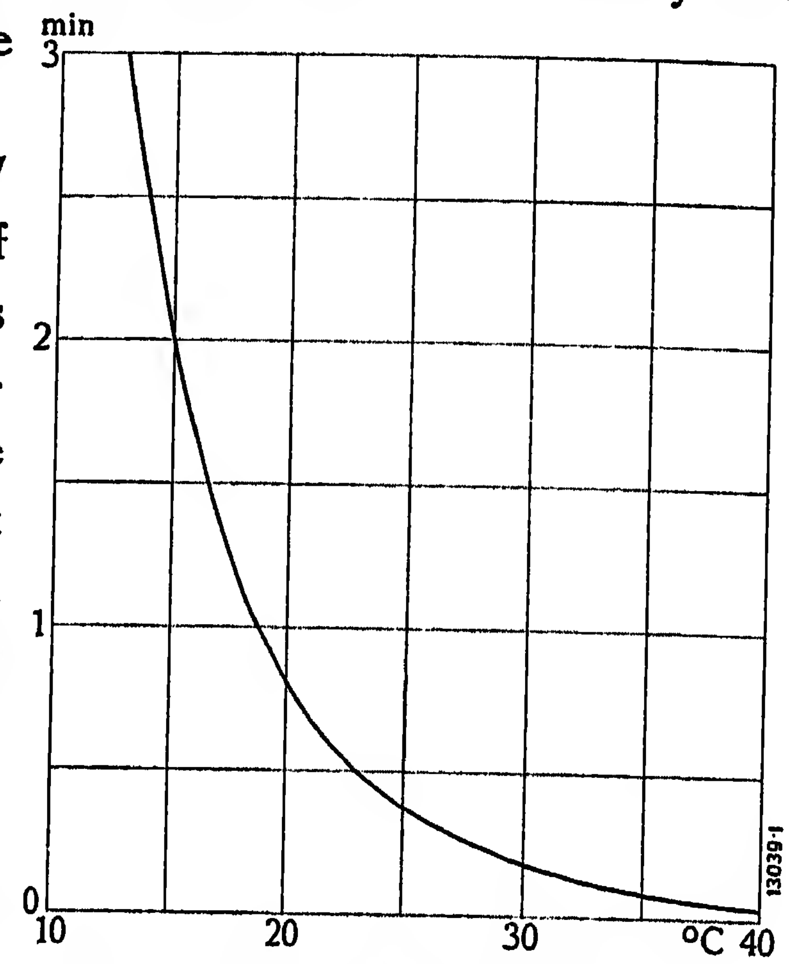


Fig. 7. — Flow curve of a resinous oil.

The typical bend of the curves is indicated very clearly in Fig. 6. It occurs within a maximum temperature variation of about 1·5° C. In order to determine exactly the setting point inside this margin, especially of oils whose setting point is not clearly defined, the following method is employed: —

The abscissae and ordinates of the flow curves are always drawn to the same scale, namely, 1° C = 1 cm and 1 sec = 1 mm. The setting point is that point on the curve where a tangent to the latter makes an angle of 45° with the axes.

A certain percentage of water in the oil, as well as keeping the oil at 110° C for several hundred hours, does not have any appreciable effect on the setting point.

This method can be used without modification to determine the setting point of other mineral oils, such as lubricating oil for bearings. For very thick oils, like cylinder oil, it is however necessary to chose another scale for the time of flow.

The new method just described has been exclusively used during the last three years by Brown Boveri, and has proved very successful for the examination of mineral oils at low temperatures.

G. B. (D. M.)

NOTES.

Voltage variations in spinning mills.

Decimal index 621.39 : 677.

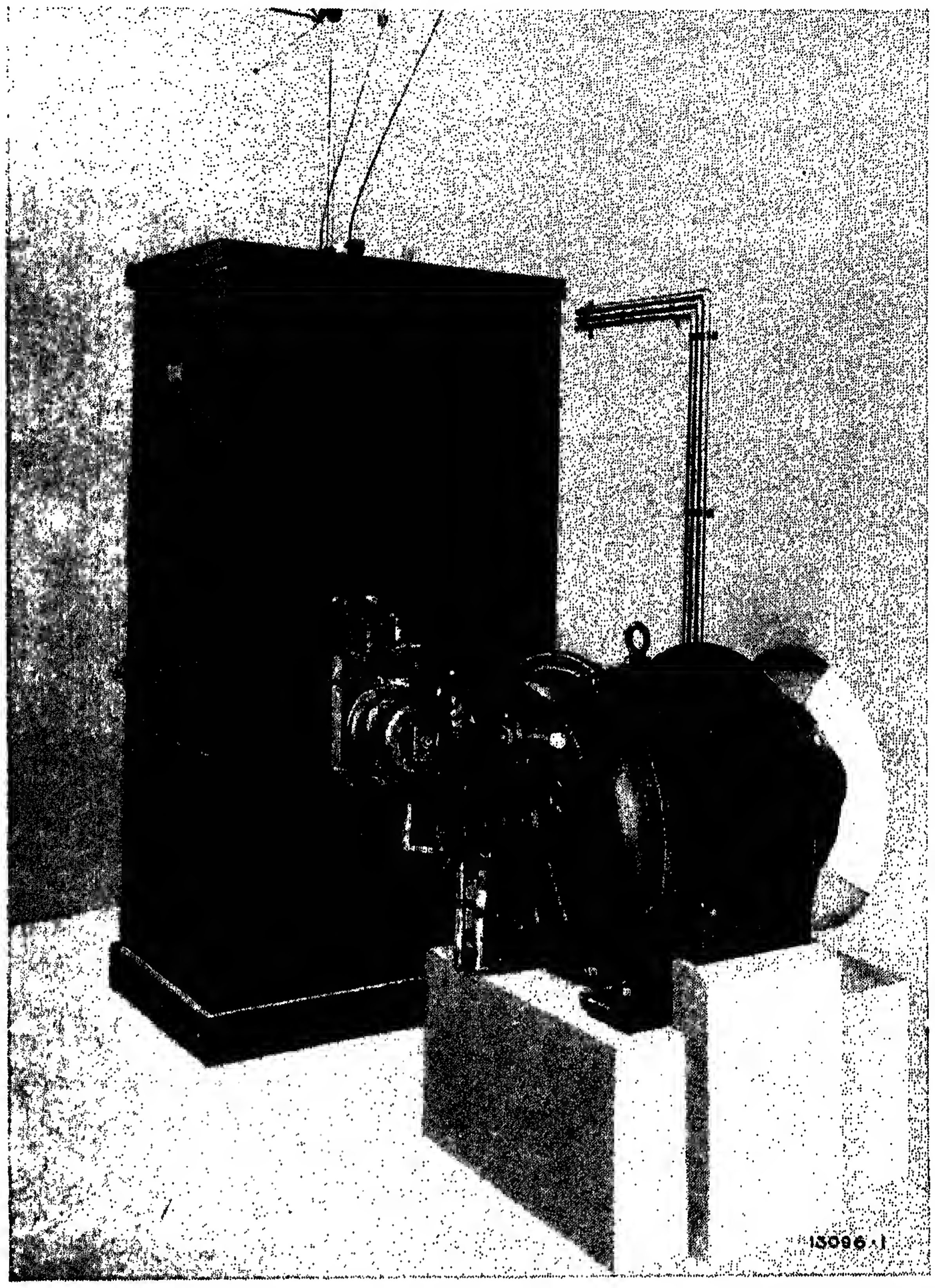
LARGE distribution systems supplying variable loads are often subject to fluctuations of voltage which cannot be obviated even by the most careful regulation in the power station. These variations are often sufficient to have undesirable consequences in certain installations connected to the system. For instance if the pressure drops too much the fuses melt and the overload releases trip, since with a constant load the current increases proportionally to the voltage drop. This entails the temporary stoppage of individual machines or even of entire groups. Besides, all motors are less efficient when they work on a higher or lower pressure than that for which they are designed. Their output varies as the square of the pressure.

In spinning mills where the ring-spinning frames are operated by A. C. commutator motors it is impossible to get the full advantage of this type of drive if the voltage at the terminals varies considerably. For this reason it is advisable to protect the motors from large voltage variations. This is rendered possible, without considerable outlay, by the induction regulators manufactured by Brown, Boveri & Co. They have been on the market several years, and the illustration shows one of these induction regulators which has been in service for a long time in the Birs spinning mills at Aesch, near Basle. These mills spin a very fine superior quality of yarn on ring-spinning frames driven by Brown Boveri single phase commutator motors whose speed is automatically governed according to the building up of the cop, so that a constant tension of the yarn and consequently a product of very even quality is obtained.

The induction regulator is in the transforming station and gives very satisfactory results. The control, by means of a Brown Boveri quick-acting voltage regulator, is entirely automatic. The pressure, which varies from 460 to 540 V, is brought practically instantaneously to a determined value. This is fixed at 500 V at no load and 515 V at full load to compensate the pressure drop between the induction regulator and the motors.

Further information concerning the details of the installation and working of Brown Boveri induction regulators will be found in the Revue BBC, 1917, No. 11, p. 260.

A. W. (D. M.)



Brown Boveri induction regulator with automatic regulating device installed at the spinning mills of the S. A. Birs.

THE INDEX OF TECHNICAL PERIODICALS no longer forms an integral part of our Review but will be issued separately every three months.

To permit of cutting out the notices for indexing purposes they will be printed on one side of the paper only. The headings will be given in English, French and German.

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Issued by BROWN, BOVERI & CO., BADEN (Switzerland). Printed by Kreis & Co., Basle.

RELAYS
FOR THE PROTECTION OF ALTERNATING-CURRENT PLANTS

BROWN, BOVERI & COMPANY

LIMITED

BADEN (SWITZERLAND)

823 E

February, 1924

CONTENTS.

RELAYS FOR THE PROTECTION OF ALTERNATING-CURRENT PLANTS.

INTRODUCTION.

The disturbances to which electrical plants are subject and which are due to a great variety of causes make special protective devices necessary. These are designed to protect the plant as a whole or certain sections of it, to guard as far as possible against damage, and to assure continuity of service or, at least, to minimise the number of service break-downs occurring.

As long as the quantities of energy being transmitted were relatively small, the distances short, and the tension low, ordinary fuses afforded sufficient protection. These fuses blew out when the current exceeded a given strength, thus cutting out the defective section, although it is true they often cut out the whole system at the same time.

The rapid and wide extension of electrical distribution systems created the need for improved and more sensitive protective devices. This requirement was the more imperative as it became clear that the actual blowing of protective fuses was in itself a cause of electrical disturbances, which, under certain circumstances, increased the damage done instead of diminishing it. Thus, a whole class of apparatus was created, which, instead of cutting out the defective sections directly, act indirectly, causing the automatic switches in the circuit to trip. These are known as relays.

Very different aims, of which only a few will be mentioned here, were responsible for the various types of relay. The strength of the current, its voltage, or its direction of flow are the principal factors determining the design of the relay (current, pressure and reverse-power relays). Another factor is the kind of tripping to be effected; tripping can take place either instantaneously, the relay acting the moment the current etc. attains the predetermined value (instantaneous relay), or after a certain delay called the time lag or time limit (time-limit relay). A third determining factor is the relation between the predetermined value of current etc. and the time limit; that is to say, whether the time limit is to remain the same whatever the excess of current etc. beyond the value set (definite time-limit relay), or if the time limit is to vary with the extent of the excess current etc. (inverse time-limit relay). The final determining factor is the manner in which it is desired to connect the relay to the circuit, that is to say, whether it is to be directly inserted in series with the main conductors (series relay), or connected to the main conductors through a current or pressure transformer (secondary relay).

By combining the characteristics of several relays in one apparatus, a considerable number of relay types can be designed. In practice, only a few designs suffice for the protection of electrial plants:

1. Series relay Type H 4, a definite time-limit, primary relay.
2. Over-current relay Type H 2, a definite time-limit, secondary relay.
3. Over-pressure relay Type H 2, a definite time-limit, secondary relay.
4. Over-current relay Type A 2, an inverse time-limit, secondary relay.
5. Over-pressure relay Type A 2, an inverse time-limit, secondary relay.
6. Reverse-power relay Type B, an inverse time-limit, secondary relay.

Apart from the relays classified above, there are various combinations of these relays which are used in practice.

In the following paragraphs these relays, their mode of operation, and pratical applications are described, together with the diagrams of connections most commonly adopted.

PRIMARY RELAYS.

SERIES RELAY, TYPE H 4.

Series relay, Type H 4, is a definite time-limit, primary relay. It is actuated by a given current, which can be set. The time limit, that is the time which elapses before the relay acts once the pick-up current is exceeded, remains the same whatever the excess of current may be. These relays are inserted directly into the high-tension circuit and are built in 22 grades corresponding to rated currents varying between 4 A and 1000 A. When the main current exceeds 1000 A, the relay is indirectly connected to the main circuit through a current transformer, which steps down the current to 5 A.

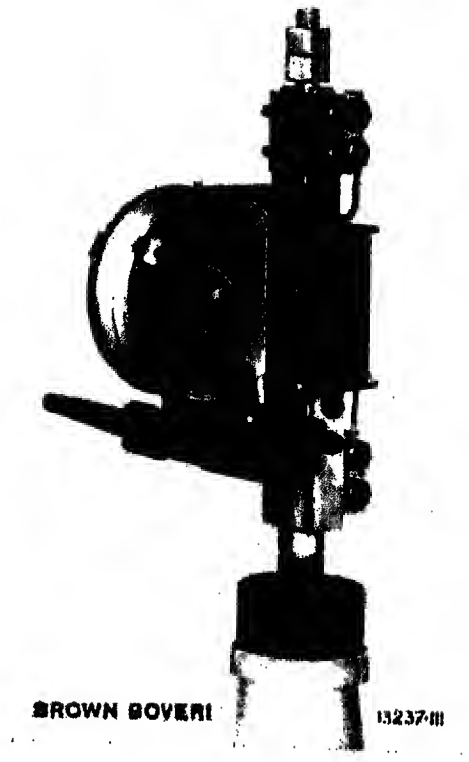


Fig. 1.
Series relay, Type H 4, for frequencies of 40 and 50 cycles.

The principal parts of the series relay are the magnet with the time-limit mechanism, the current coil, which is wound over the magnet, and the connections. The magnet consists of a laminated U-shaped iron core a, which has a laminated armature b mounted on a spindle t round which it can rotate. The time-limit mechanism is driven by a small, squirrel-cage motor built into the magnetic circuit of the core a. The worm d_1 on the motor shaft is permanently in mesh with worm wheel g_1, on the shaft of which is also mounted a pinion g. Opposite, but not in mesh with g is a toothed sector h carried by the lever k. This lever is held pressed against the upper arm of the iron core a, by the spring m, called the current spring. In this position the lever k holds the sector h out of mesh with g, as said before, and also, by means of the projection k, which engages the stop pin d_2, prevents the motor d from revolving. On the same spindle as the sector h, a pawl n is mounted, which engages a flat spring attached to the lever p; the latter is also connected to the armature b by a spring q. According to whether the screw r is placed in the treaded hole IV or V, the tripping lever b_1 is rigidly connected either to the lever p, or to the armature b. Finally, the sector h carries a pin which, when once

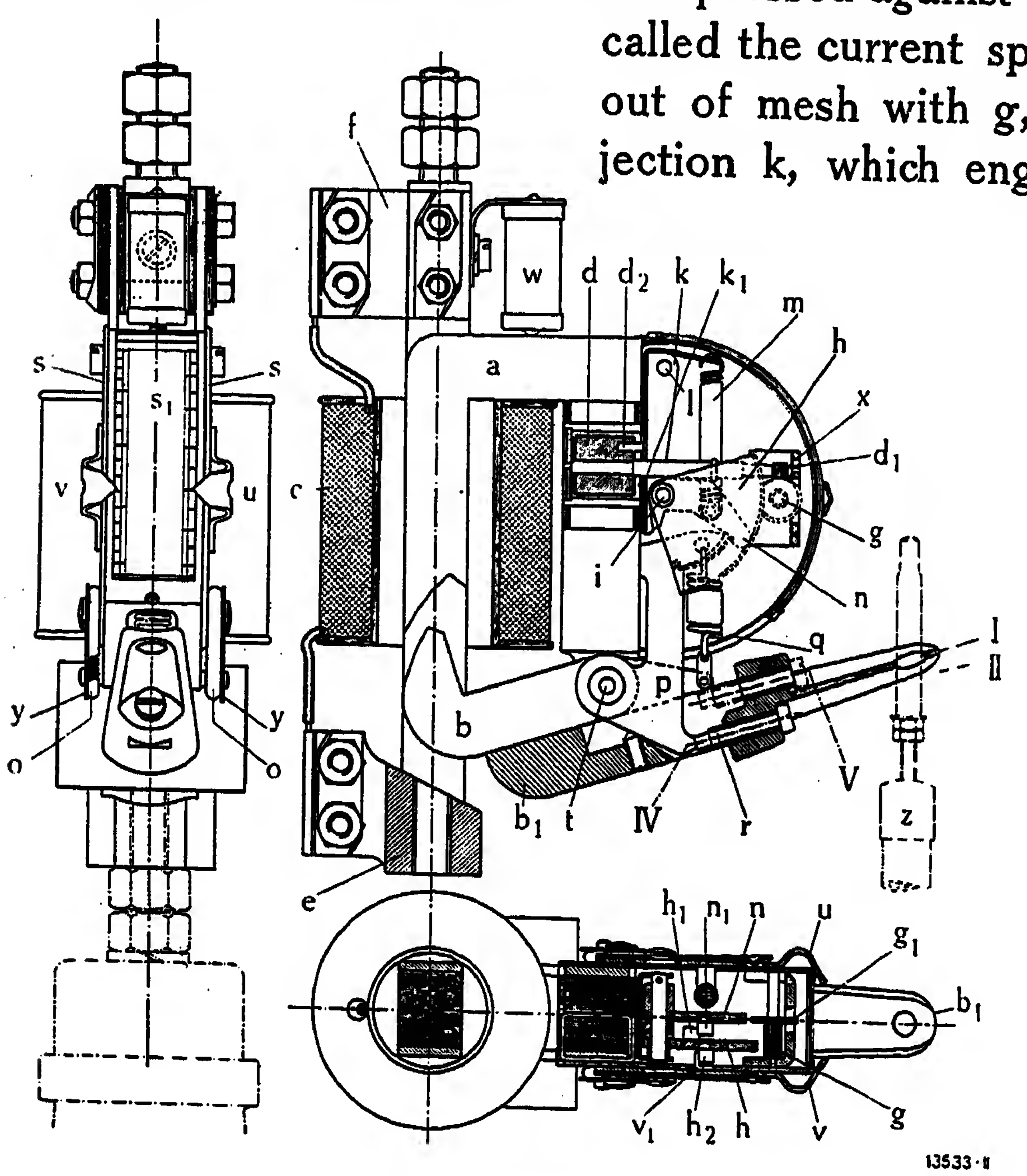


Fig. 2. **Series relay, Type H 4.**

a. U-shaped iron core of magnet.
b. Armature of magnet.
b_1. Tripping lever.
c. Current coil.
d. Motor.
d_1. Worm on motor spindle.
d_2. Stop pin on motor.
e. Terminal.
f. Terminal.
g. Pinion.
g_1. Worm wheel.
h. Toothed sector.
h_1. Pin on sector h.
h_2. Pin on sector h.
i. Spindle of sector h.
k. Movable lever.
k_1. Projection on lever k.
l. Bolt forming spindle of lever k.
m. Current spring.
n. Pawl.
n_1. Pin on pawl n.
o. Springs supporting spindle.
p. Lever.
q. Short-circuit spring.
r. Screw.
s. Cover plates of time-limit mechanism.
s_1. Front plate of time-limit mechanism with current and time-limit scales.
t. Spindle of armature b.
u. Pointer for current setting.
v. Pointer for time-limit setting.
v_1. Projection on pointer v.
w. Protecting resistance.
x. U-shaped support carrying pinion spindle.
y. Cover plate of springs o.
z. Tripping rod.
I and II. Positions of tripping lever b_1.
IV and V. Positions of screw.

the sector is raised to its highest position, acts on the catch between the pawl n and the lever p, releasing the latter. The working of the relay is explained further on.

For frequencies of $16^2/_3$ and 25 cycles per second the armature b is provided with two weights to damp its vibration.

The time-limit mechanism is covered in by a housing which protects the relay from dust as far as possible. On the front of the housing is the scale plate carrying, on the right, a current scale in amperes and, on the left, the time-limit scale divided into seconds. The scales are large and clearly visible and permit very precise adjustment. The pointer u is for the current setting and stretches the current spring m more or less, which means that the strength of current necessary to overcome the force of the spring is increased or reduced. The pointer v is for the time-limit setting and acts on the segment h, raising or lowering it, and this lengthens or shortens the time limit of the relay.

The current coils can easily be changed. A protective resistance w can be connected in parallel with the current coil, with the object of diverting pressure surges and preventing flash-overs. This protective resistance is necessary for all rated pressures exceeding 12'000 volts and also for lower pressures, when no other form of protection is provided for the relay.

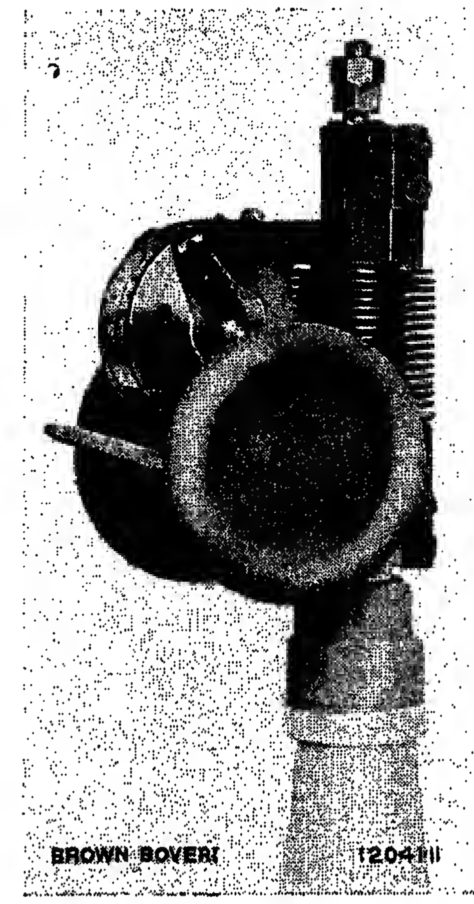


Fig. 3.
Series relay, Type H 4, for $16^2/_3$ and 25 cycles.

For rated pressures exceeding 80'000 volts, with frequencies of 40 and 50 cycles, the series relays are equipped with a sheet-metal hood as a protection against silent discharges.

The terminals e and f are located on the iron core of the magnet, to which they are bolted, for currents up to 600 amps. These terminals are supplied, according to current strength, in three different thread diameters and can be interchanged if desired.

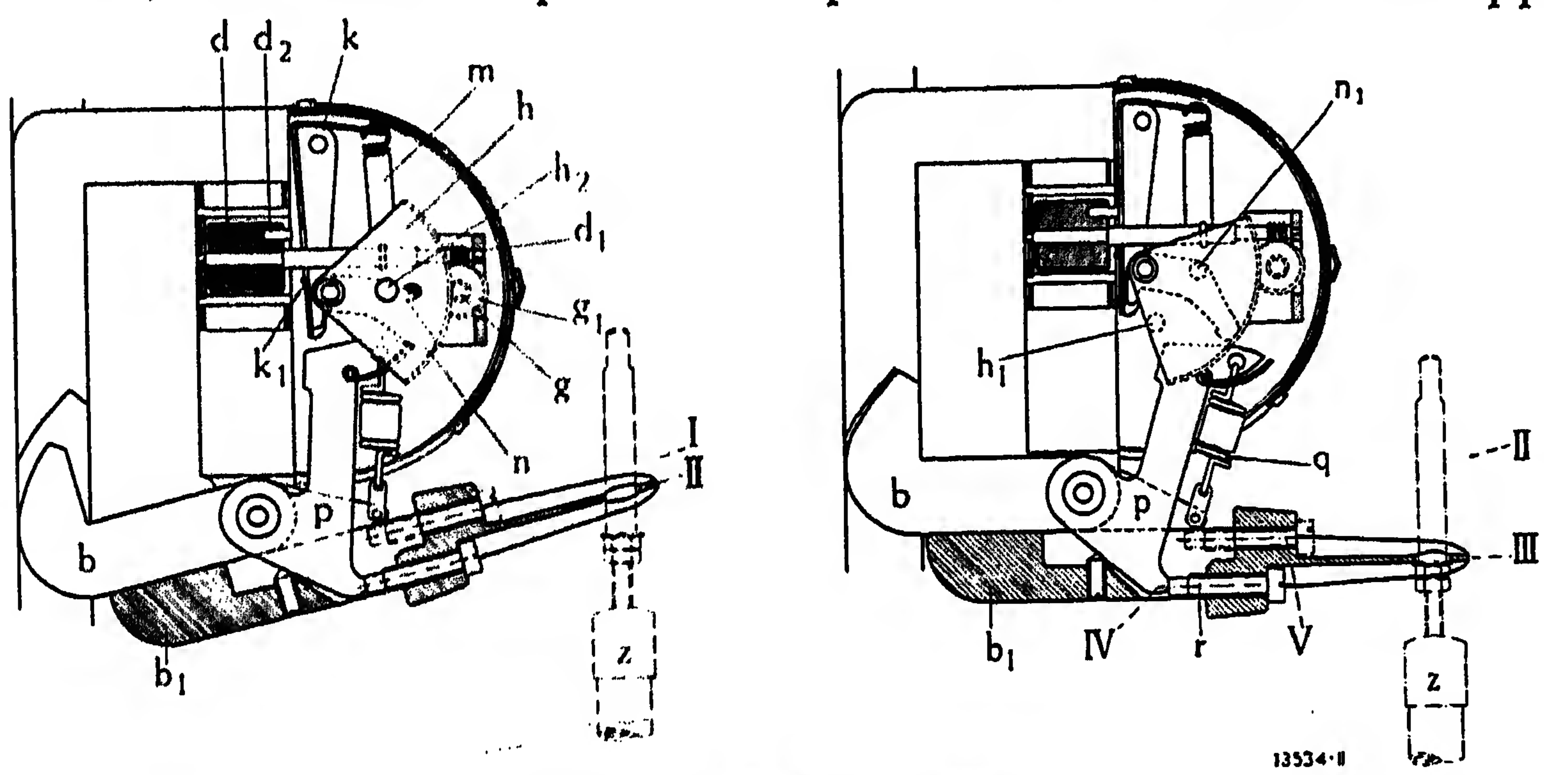


Fig. 4. Series relay, Type H 4,
Tripping lever b_1 in position II during tripping. Tripping lever b_1 in position III tripped.

The manner in which the relay operates may be described as follows: —

First, consider conditions when the screw r is placed in hole IV. If the pick-up current is exceeded, the pull of the current spring m is overcome by the attraction of the armature b to the magnetised core, so that tripping lever b_1 rotates about t until it reaches position II. At the same time toothed segment h moves forward until it meshes with pinion g and the motor d is freed from the projection k_1 by the movement of the lever k. The motor revolves and raises the toothed sector h. On reaching its highest position, the latter releases the pawl n which has been retaining the lever b and the tripping lever b_1. Under the pull of spring q, the tripping lever, which is now freed, strikes the tripping rod z a sharp blow, causing it to release the switch. After this has been effected, the current spring m brings the tripping mechanism back to its original position, in other words, resets the relay for a second tripping. This also happens if, during the time the relay is in action and before it has tripped, the strength of the current should again fall below the pick-up value.

Consider, now, the case of the screw r in hole V. The tripping lever b_1 is now a rigid part of lever b and its movement is no longer dependent on the lever p. On the occurrence of

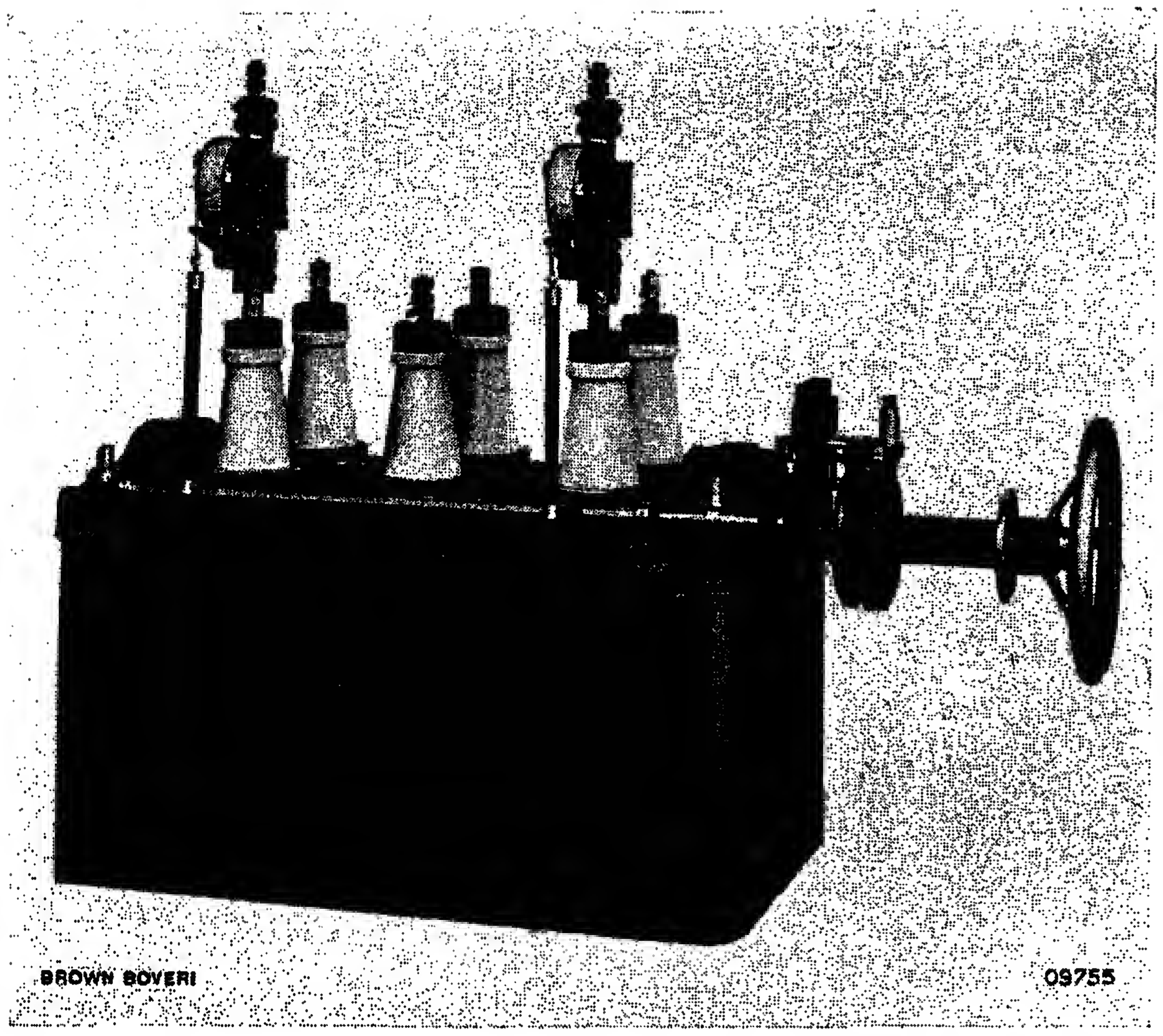


Fig. 5. Three-pole oil switch with front control and series-relay release on two poles.

a short circuit exceeding three times the normal current, the two levers are attracted to full extent and the switch is tripped instantaneously.

Series relays are generally bolted directly to the terminal bolts of oil switches, which they trip, either mechanically through the agency of a trip rod, or electrically by means of a contact. The very narrow construction of these relays and their small overall dimensions allow of mounting them on an oil switch without encroaching on the specified clearance between poles. The arrangement of the terminals in the axis of the leads make for a neat lay out of the conductors however massive they may be.

The tripping current of the relay can be set at from 1·4 to twice the normal current of the relay. The time limit can be set approximately between the limits of 1 and 40 seconds, according to frequency. For special conditions, the time limit can be made 9 or 15 times longer than the normal, by using an intermediate gear. Should the current fall below the pick-up value, the relay stops and returns to its initial position.

Series relays, Type H4, can be used for the protection of most plants, whether power stations, sub-stations, or power consumers' installations. When, however, the switches to be released are on connecting lines between various power stations, or on ring systems or parallel conductors, each case must be studied individually to ascertain whether inverse time-limit relays would not be more suitable.

By suitably graduating the time limits of the various relays on a circuit, it is possible to make them trip in a given sequence in all cases of disturbance and to cut out the defective section of the circuit.

As no current transformer, tripping solenoid, or auxiliary source of current is required with series relays, they make the installation simple and cheap, but nevertheless quite reliable. The fact that several thousands of H4-Type relays are supplied each year is a proof that their great mechanical and electrical advantages are fully recognised and appreciated. These advantages are summarised below.

(a) Mechanical advantages.

1. Enclosed mechanism, protected as far as possible from dust.
2. Large, clear, time and current scales permitting accurate setting.
3. Compact design resulting in small overall dimensions so that, when mounted on an oil switch, the prescribed clearance between poles is not encroached upon.
4. Possibility of making a neat layout of conductors, however massive, because the relay terminals are in the axis of the leads.
5. Simplicity of layout owing to the absence of current transformers, releasing magnets, and auxiliary sources of current.

(b) Electrical advantages.

1. Tripping effected by sharp blow of releasing lever, therefore certain action.
2. No operation if current falls below the pick-up value before the time limit has elapsed, therefore no unnecessary tripping.
3. Time limit independent of the value of excess current, so that, with suitable graduation of the time limits, the oil switches on a line section trip in a given sequence under all disturbances.
4. The relay can be set for instantaneous tripping when a short circuit occurs.

SECONDARY RELAYS.

TRIPPING METHODS.

As already explained, series relays are inserted in the leads themselves and trip the oil switch by a hammer-like blow delivered by the tripping lever which is part of the relay. With secondary relays, on the other hand, the coils of the relay are not inserted in the leads but are connected to them through current or pressure transformers. The tripping of the switch is generally electrical, that is to say, the relay either makes or breaks an auxiliary circuit in which a special device for tripping the oil switch is connected. These relays are, therefore, classed as relays with closing contact and relays with opening contact.

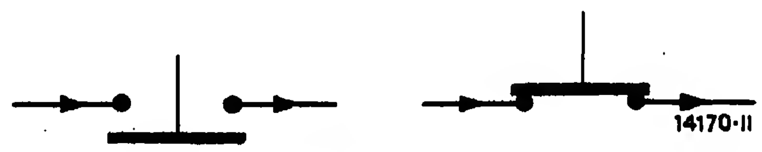


Fig. 6.
Closing contact. Opening contact.
Movable contact in normal position.

According to the kind of current available, and to the kind of plant to be protected, the following systems of connections are used:—

1. Auxiliary-current tripping.

The source of auxiliary current used to trip the switch must be entirely independent of the plant to be protected. The current can be either direct or alternating, the most suitable being direct current from a storage battery used for general purposes on the station, or from either a small storage battery or a battery of primary cells specially installed for tripping purposes only. An independently driven generator or a transformer fed by another station can also be used, but a generator driven by a motor which is itself fed from the bars of the station to be protected is not suitable.

The following diagrams show the connections for over-current relays, over-pressure relays and reverse-power relays. The switch is of the hand-control type with tripping solenoid. The circuit of the latter is closed by the relay contacts (closing contacts), thus tripping the switch. This switch can also be tripped by means of a push-button switch in parallel with the relay

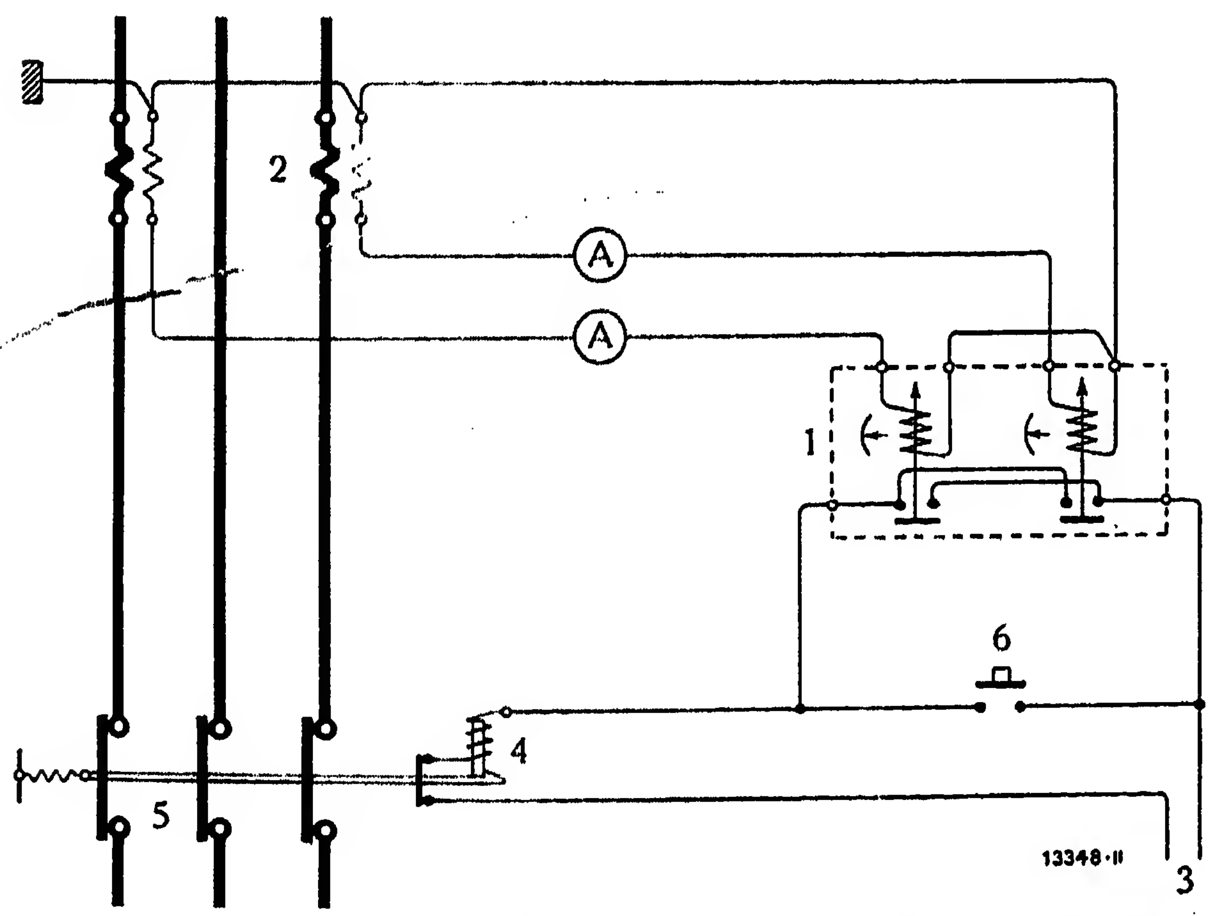


Fig. 7. Diagram of connections for over-current relay with auxiliary-current tripping.

1. Over-current relay with closing contact. 2. Current transformers. 3. To the auxiliary current supply. 4. Tripping solenoid with auxiliary contacts. 5. Oil switch. 6. Push-button switch with closing contacts.

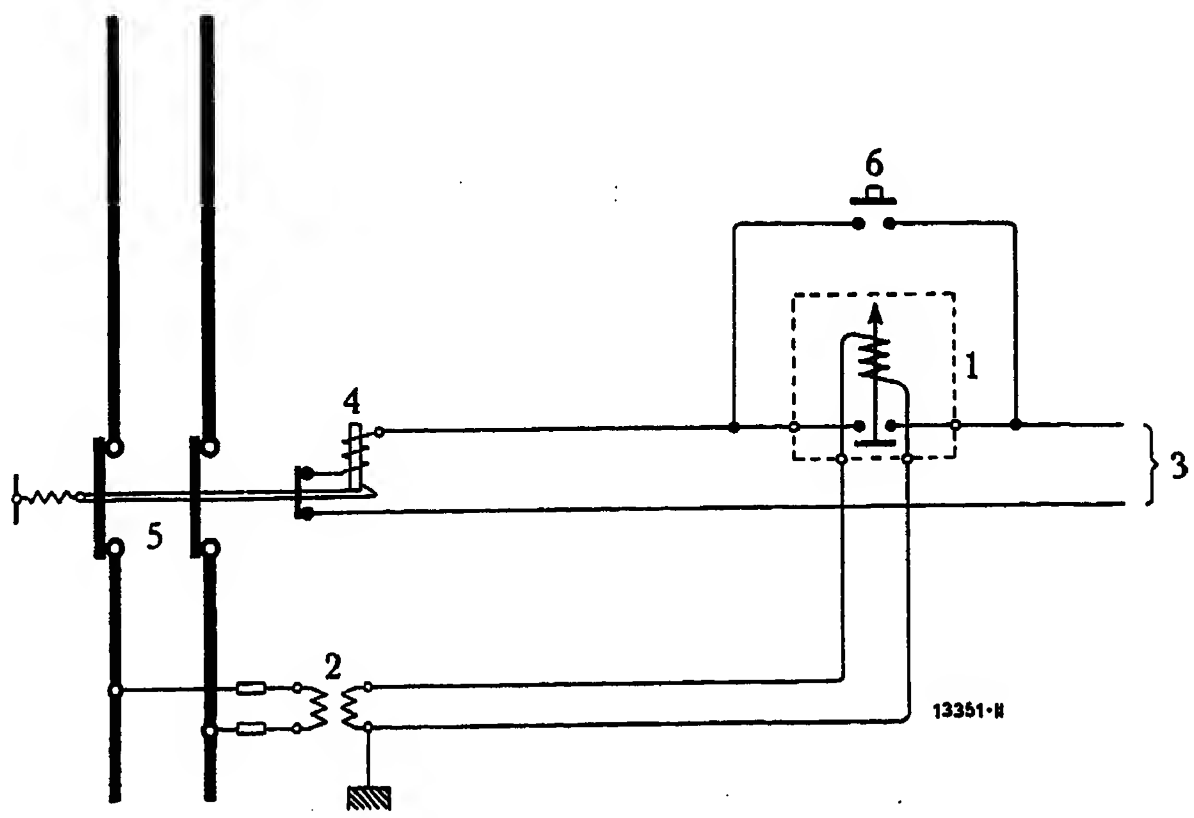


Fig. 8. Diagram of connections for over-pressure relay with auxiliary-current tripping.

1. Over-pressure relay with closing contact. 2. Pressure transformer. 3. To the auxiliary current supply. 4. Tripping solenoid with auxiliary contacts. 5. Oil switch. 6. Push-button switch with closing contacts.

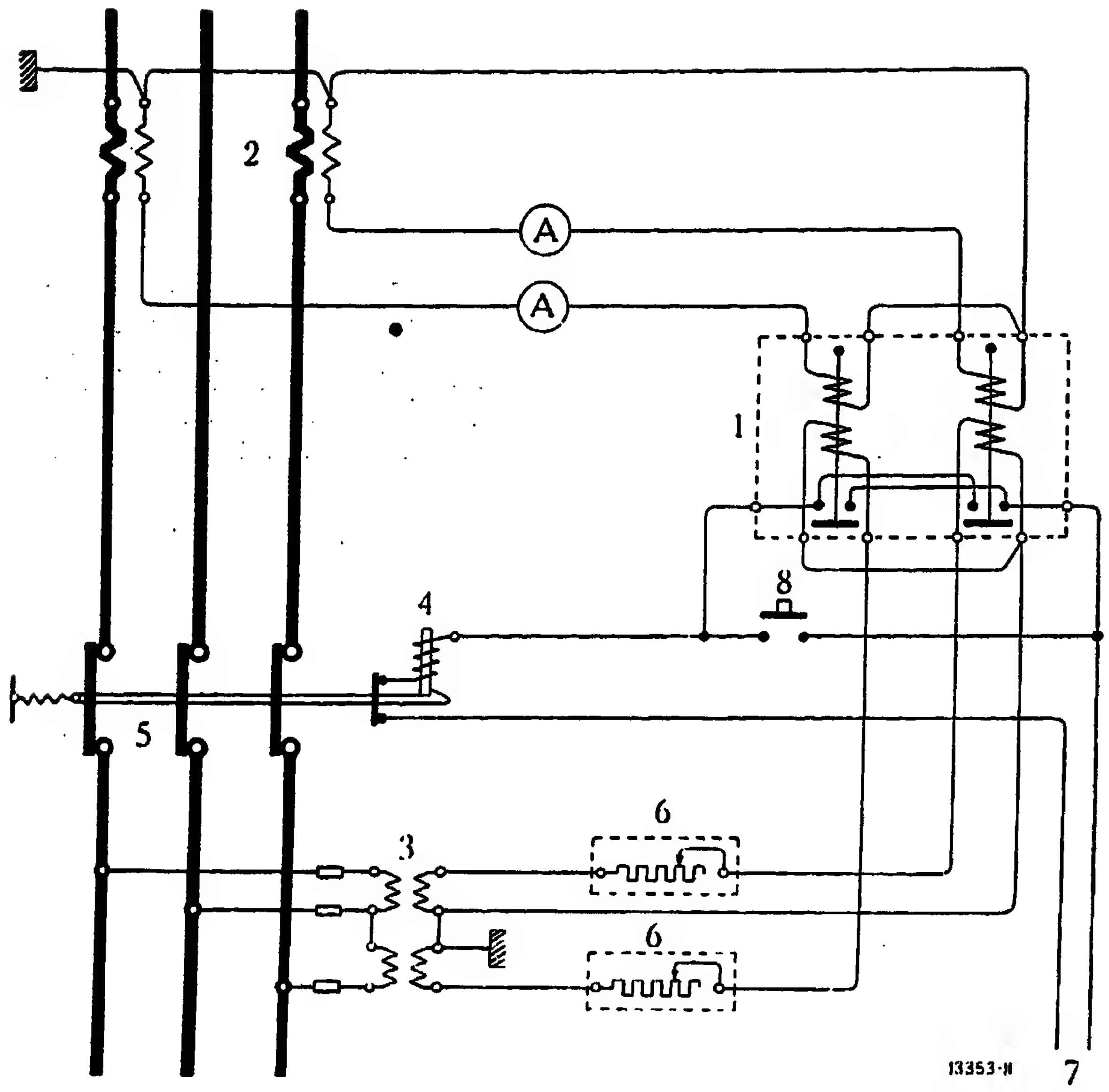


Fig. 9. **Diagram of connections for reverse-power relay with auxiliary-current tripping.**

1. Reverse-power relay with closing contact. 2. Current transformers. 3. Pressure transformers. 4. Tripping solenoid with auxiliary contact. 5. Oil switch. 6. Series resistances. 7. To the auxiliary current supply. 8. Push-button switch with closing contacts.

contacts and placed in any desired position in the plant. After tripping has taken place, the circuit of the tripping solenoid should not be broken again by the relay contacts, but by a special auxiliary contact on the shaft of the oil switch, of the type used on Brown Boveri hand-operated gears with solenoid release, or on solenoid and motor remote-control gears, for example.

Auxiliary-current tripping can be of single, two, or three-pole type. If a neutral point of the system is earthed, three-pole protection is required; if a neutral point is not earthed two-pole protection is sufficient for three-phase systems.

2. Tripping by means of a current transformer.

In this case, the current necessary for releasing the switch is obtained from a current transformer. Normally, the relay contacts shunt the tripping solenoid, but when the relay coils are subjected to an excessive current, the contacts open and the current of the transformer must pass through the tripping solenoid (opening contacts). In order to prevent the welding together of the relay contacts, which may possibly occur if the current broken is heavy, this method of tripping must be used judiciously and only when an auxiliary source of current is not available, where no-volt tripping is undesirable, and where, for special reasons, series relays are unsuitable. This method of tripping is only suitable for over-current relays. It can be used for one or two-poles, but not for three.

As the short-circuit current to which the relay is subjected varies according to the position of the current transformers, two different systems of connections are employed:—

(a) Relay current transformer tripping. This system is admissible in plants where short-circuit currents of more than 6 times the rated current are not probable. The ratio of the current transformer must be such that it steps down to 1 A, and the tripping solenoid coil and the relay coils must be wound for that current.

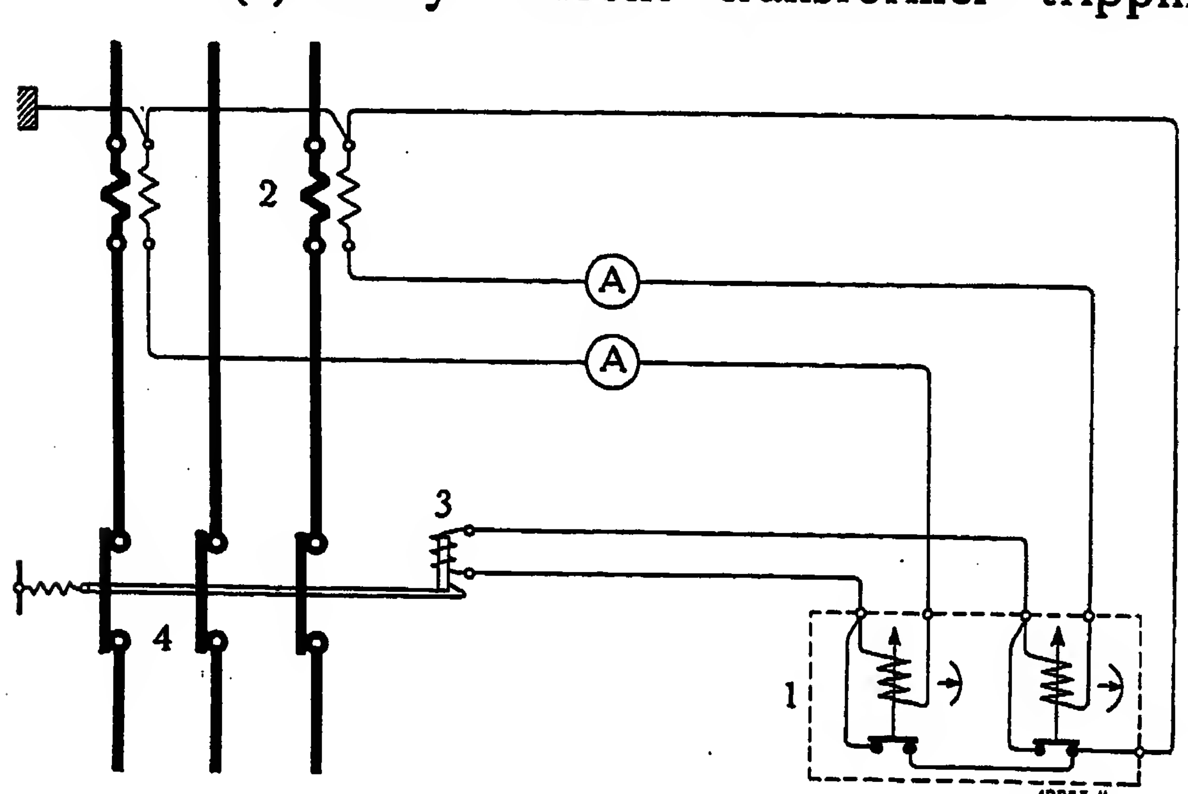


Fig. 10. **Diagram of connections for over-current relay with relay current transformer tripping.**

1. Over-current relay with opening contact. 2. Current transformers. 3. Tripping solenoid. 4. Oil switch.

(b) Auxiliary current transformer tripping. If the short-circuit currents to be dealt with are likely to exceed 6 times the rated value, an auxiliary current transformer must be added. This is so built that however heavy the short-circuit current on the primary side, the current on the secondary side cannot exceed an admis-

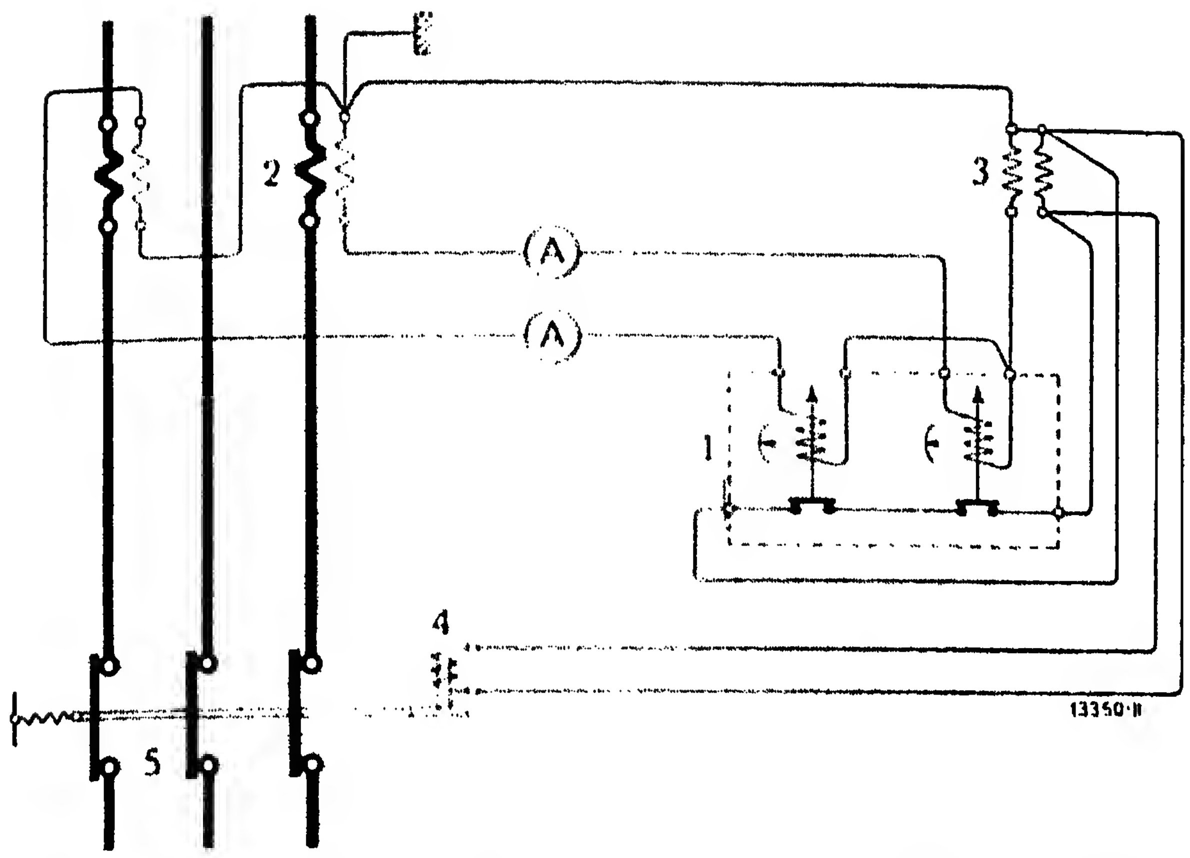


Fig. 11. **Diagram of connections for over-current relay with auxiliary current transformer tripping.**

1. Over-current relay with opening contact. 2. Current transformers. 3. Auxiliary current transformer. 4. Tripping solenoid. 5. Oil switch.

sible value. Thus, when a short circuit occurs, the relay contacts are protected against overheating before they open and against excessive arcing when they break.

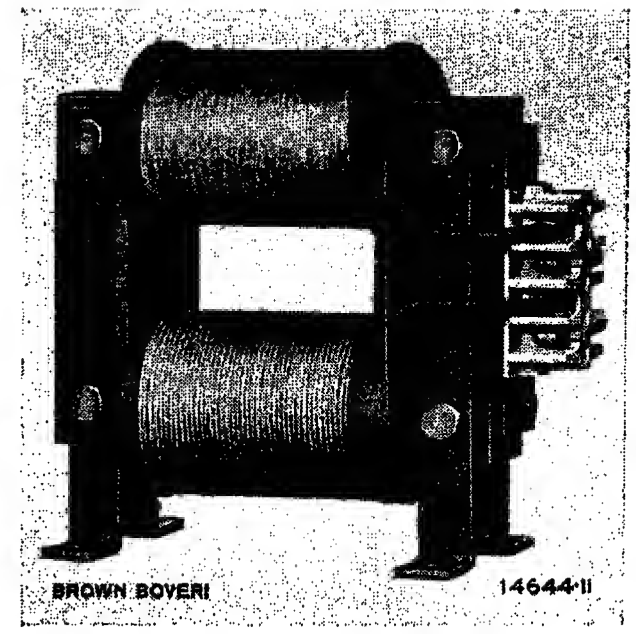


Fig. 12.
Auxiliary current transformer, Type CZ 2.

The ratio of the auxiliary current transformer must be such that 1 A is delivered on the secondary side, even if the relay current transformer steps down to 1 A. This system of tripping cannot be used on three poles.

3. *Under-pressure tripping.*

This is only used in conjunction with over-current relays. The tripping solenoid is supplied by the secondary winding of a pressure transformer, the circuit of which is completed through the relay contacts (opening contacts). Thus, the armature of the solenoid is held closed under normal conditions. If the pressure falls very considerably, the armature falls and trips the switch. The same thing occurs if excessive current passes through the coils of the over-current relay and breaks the circuit by opening the contacts. By means of a push-button switch, tripping can be effected from any desired point in the station.

Under-pressure tripping is principally employed to protect consumers' plants in cases where it is necessary to cut out and restart the motors in the event of a temporary drop in the pressure. It is unsuitable for the protection of transformers in transformer stations because, during a short circuit, not only the switch on the overloaded line would be tripped by the over-current relay, but all the other switches as well, owing to the pressure drop during the short circuit.

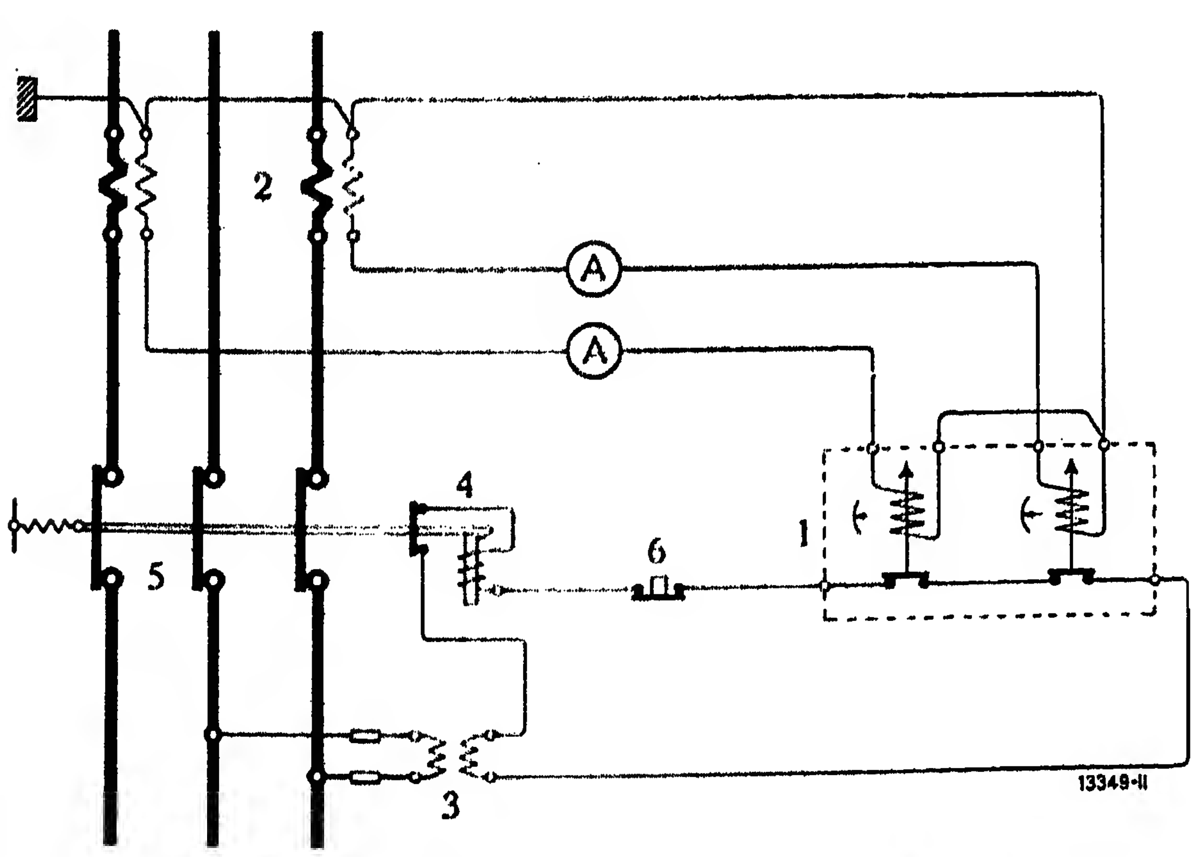


Fig. 13. **Diagram of connections for over-current relay with under-pressure tripping.**

1. Over-current relay with opening contact. 2. Current transformers. 3. Pressure transformer. 4. Tripping solenoid with auxiliary contacts. 5. Oil switch. 6. Push-button switch with opening contact.

With machines which remain excited during shutting down, such as synchronous motors, rotary converters, etc. the pressure drops with the frequency. The excitation of the tripping solenoid remains the same in spite of the decrease in speed, so that the switch is only tripped when the machine under consideration is almost at a standstill. To make the tripping independent of the frequency, an ohmic resistance is placed in series with the tripping solenoid. The under-pressure system of tripping can be carried out on one, two, or three poles.

Fig. 14.
Series resistance, Type K.

OVER-CURRENT RELAY, TYPE H 2.

Over-current relay Type H 2 is a definite time-limit, secondary relay. As Fig. 15 shows, it is built on the principle of series relay H 4, being composed of the same principal components, and differing from the latter only in those details requisite to make it a secondary relay.

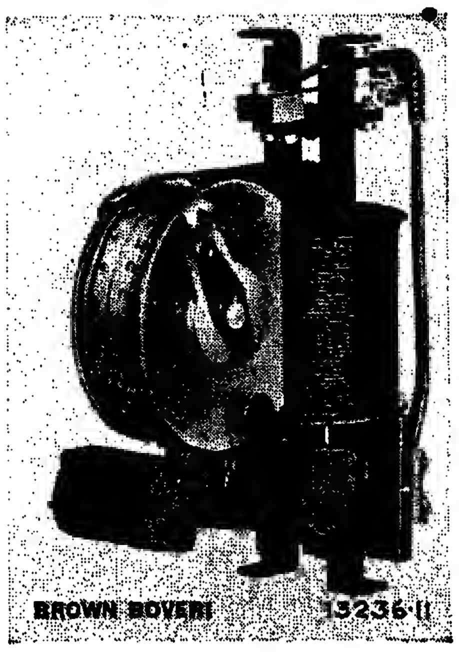


Fig. 15.
Over-current relay, Type H 2, for frequencies of 40 and 50 cycles (without casing).

The current coil is wound for a normal current rating of 5 A and, exceptionally, for 1 A and $1 \times \sqrt{3}$ A.

Instead of direct mechanical tripping, the relay is built for indirect tripping, which it effects by the closing or opening of the contact e, secured to the armature a and operated by the insulated rod f, which is itself controlled by the tripping lever b_1.

If required, the relay can be fitted with a device to show that it has tripped. This consists of a shutter w, pivoted on the lever b_1, and held in position by the stop w_1. When the relay acts, this shutter drops. It must be set again by hand.

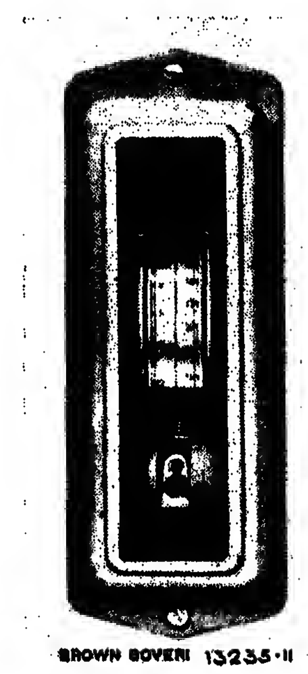


Fig. 17.
Over-current relay. Type H 2, for frequencies of 40 and 50 cycles (with casing).

For 40 and 50 cycles, the relay is of single-pole type fitted in a sheet-metal casing designed to be mounted flush with the instrument panel of a switchboard.

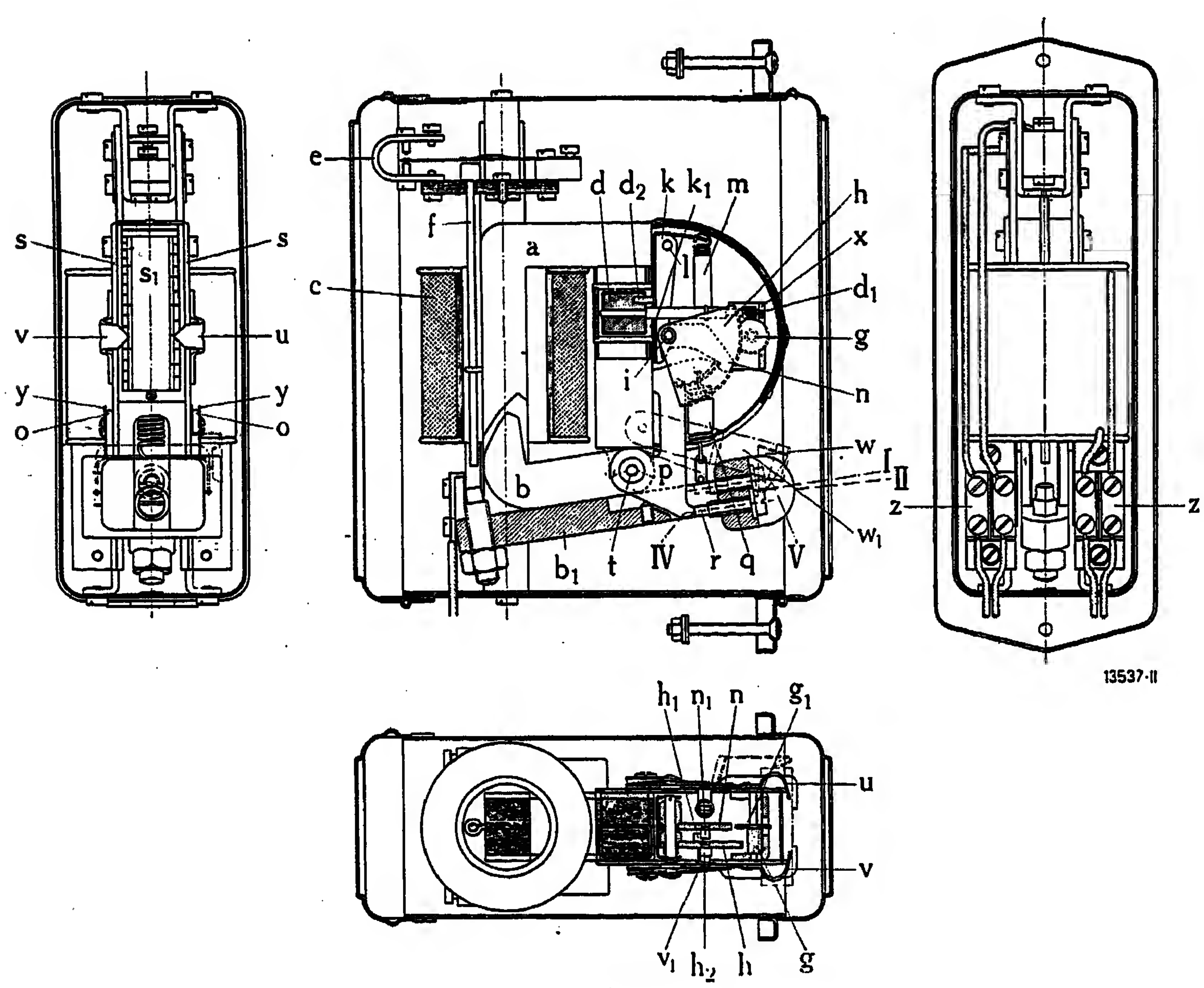


Fig. 16. Over-current relay, Type H 2.

a. U-shaped iron core of magnet.
b. Armature of magnet.
b_1. Tripping lever.
c. Current coil.
d. Motor.
d_1. Worm on motor spindle.
d_2. Stop-pin on motor.
e. Contact.
f. Insulated rod.
g. Pinion.
g_1. Worm wheel.
h. Toothed sector.
h_1. Pin on sector h.
h_2. Pin on sector h.
i. Spindle of sector h.
k. Movable lever.
k_1. Projection on lever k.
l. Bolt forming spindle of lever k.
m. Current spring.
n. Pawl.
n_1. Pin on pawl.
o. Springs supporting spindle t.
p. Lever.
q. Short-circuit spring.
r. Screw.
s. Cover plates of time-limit mechanism.
s_1. Front plate of time-limit mechanism.
t. Spindle of armature b.
u. Pointer for current setting.
v. Pointer for time-limit setting.
v_1. Projection on pointer v.
w. Shutter.
w_1. Stop.
x. U-shaped support of pinion spindle g.
y. Cover plate of spring o.
z. Terminals.
I and II. Positions of tripping lever b_1.
IV and V. Positions of screw.

The relays for 25 and 16 ²/₃ cycles have weights to damp vibration and are provided with wider casings of either the raised or the flush type, holding one, two, or three relays. These relays can only be mounted vertically.

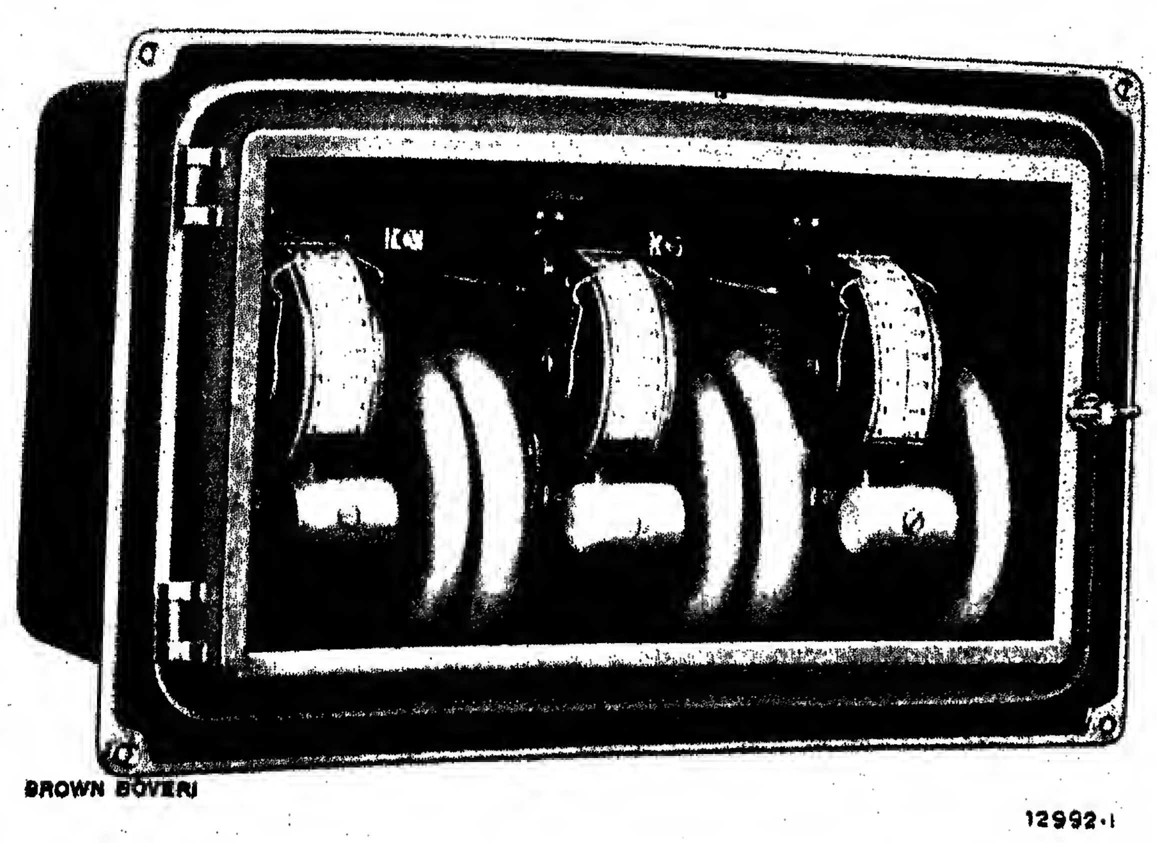


Fig. 18. Over-current relay, Type H 2, for frequencies of $16^{2}/_{3}$ and 25 cycles, with flush-type casing.

The pick-up current can be set between 1·3 and twice the rated current. The range of adjustment of the time limit is similar to that of the relay H 4 and can, if required, be extended by the addition of an intermediate gear.

Should the current fall below the pick-up value, the relay stops and returns to its initial position.

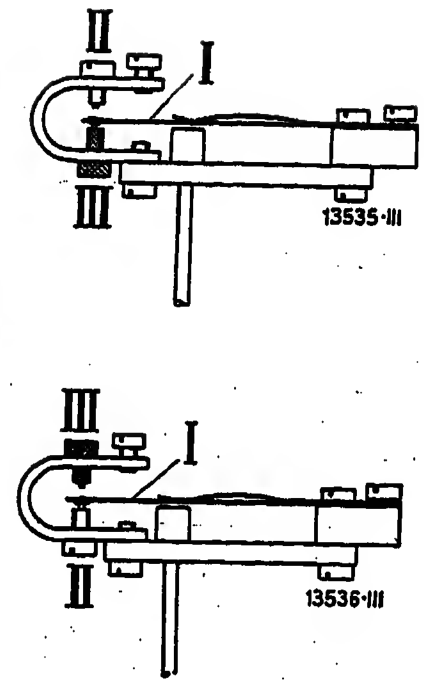


Fig. 19.

Closing contact and opening contact.

I. Contact spring.
II. Screw with platinum tip.
III. Screw with ivory tip.

Over-current relay H2 can be used with every method of tripping. The power when tripping with direct current should not exceed about 500 watts, and with alternating current 300 VA.

The field of application of relay H 2 is the same as that of relay H 4, but, being a secondary relay, it is particularly suitable for plants where the control instruments are centralised.

Although not so generally used as relay H 4, relay H 2 is to-day widely employed, thanks to its great advantages, of which the chief are:—

(a) Large, clear, current and time scales, permitting accurate setting.

(b) Wide range of adjustment both for current and time limit.

(c) No operation if the current drops below the pick-up value, that is, no unnecessary tripping.

(d) Time limit independent of the value of excess current, so that, if the time setting of the relays of the various switches on a section of distribution system are suitably graded, the switches will trip in a given sequence, whatever trouble arises.

(e) The relay can be set to trip instantaneously on short circuits.

(f) Compactness of design.

OVER-PRESSURE RELAY, TYPE H 2.

Over-pressure relay Type H 2 is a definite time, secondary relay, identical in design to the over-current relay H 2 except that the current coil is replaced by a pressure coil. The screw r is always left in the hole IV of the lever b_1.

The tripping pressure can be set between 1·35 and 1·9 times the rated pressure. The time limit has a range of adjustment of about 1 to 12 seconds for 50 cycles, 1 to 18 seconds for 40 cycles, and 4 40 seconds for $16^{2}/_{3}$ cycles. The relay is only supplied for auxiliary-current tripping with closing contact.

Over-pressure relay H 2 is used to actuate alarm devices when the pressure becomes excessive, or to prevent the rise in pressure by tripping automatic switches.

In power stations, it is connected to the terminals of the generator, its duty being to demagnetise the latter by tripping the field switch, in the event of the generator for any reason attaining an excessive speed. If a prime mover runs away, it is possible — particularly with alternators equipped with direct-coupled exciters — that the pressure may reach such a high value that even the automatic pressure regulator cannot reduce it. As, in such cases, the frequency also rises, the magnetisation of the relay is no greater, despite the increase in pressure, and the relay does not function. It is, therefore, necessary to make the relay act independently of the change in frequency, which is done by placing an ohmic resistance in series with the coil.

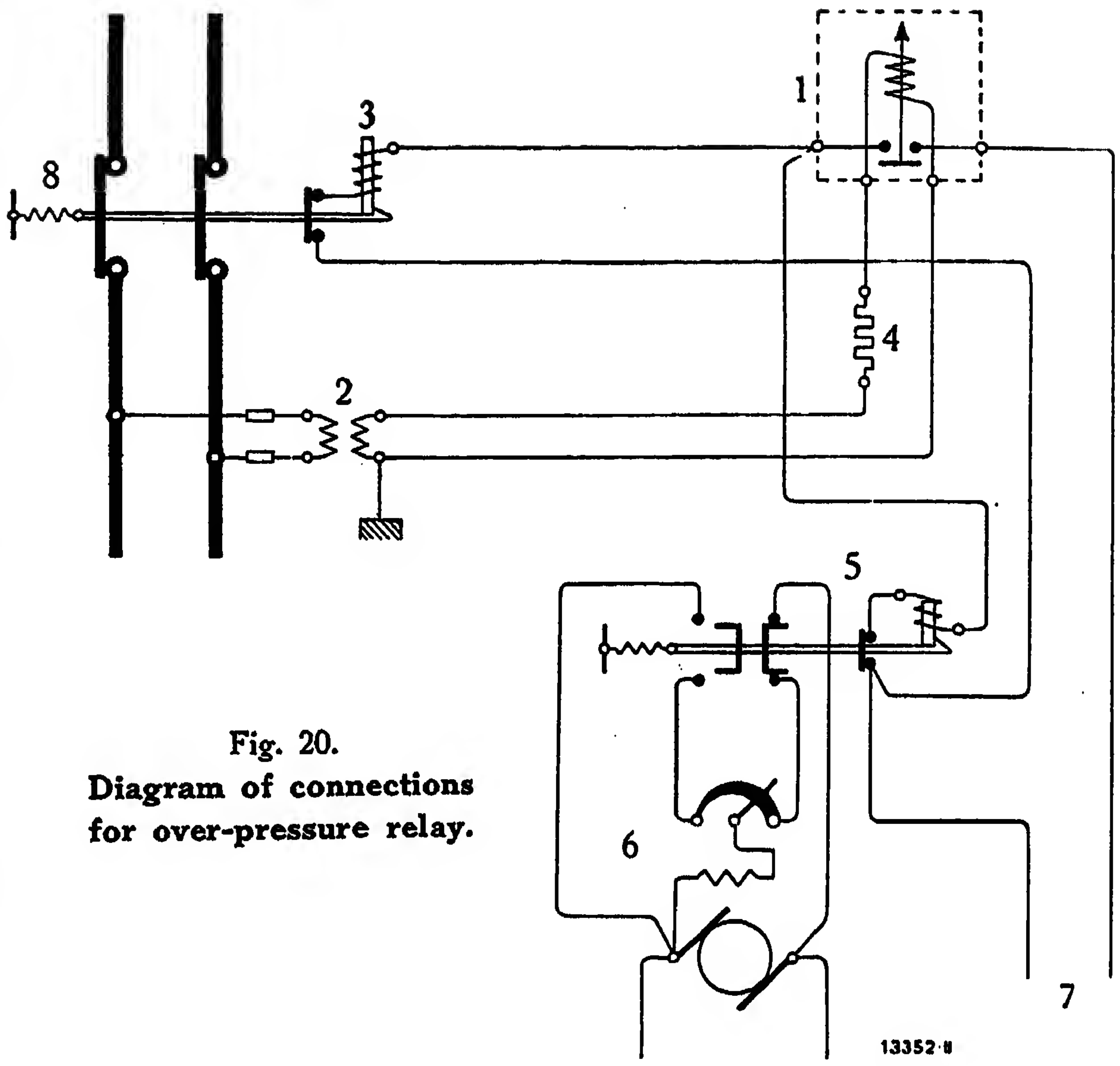


Fig. 20.
Diagram of connections for over-pressure relay.

1. Over-pressure relay with closing contact. 2. Pressure transformer. 3. Tripping solenoid with auxiliary contacts. 4. Series resistance. 5. Switch in exciter field. 6. Exciter with field rheostat. 7. To the auxiliary current supply. 8. Oil switch.

OVER-CURRENT RELAY, TYPE A 2.

Over-current relay Type A 2 is an inverse time, secondary relay. It acts under a given current, but the time limit varies according to the value of the excess current: the stronger the excess current the shorter the time limit.

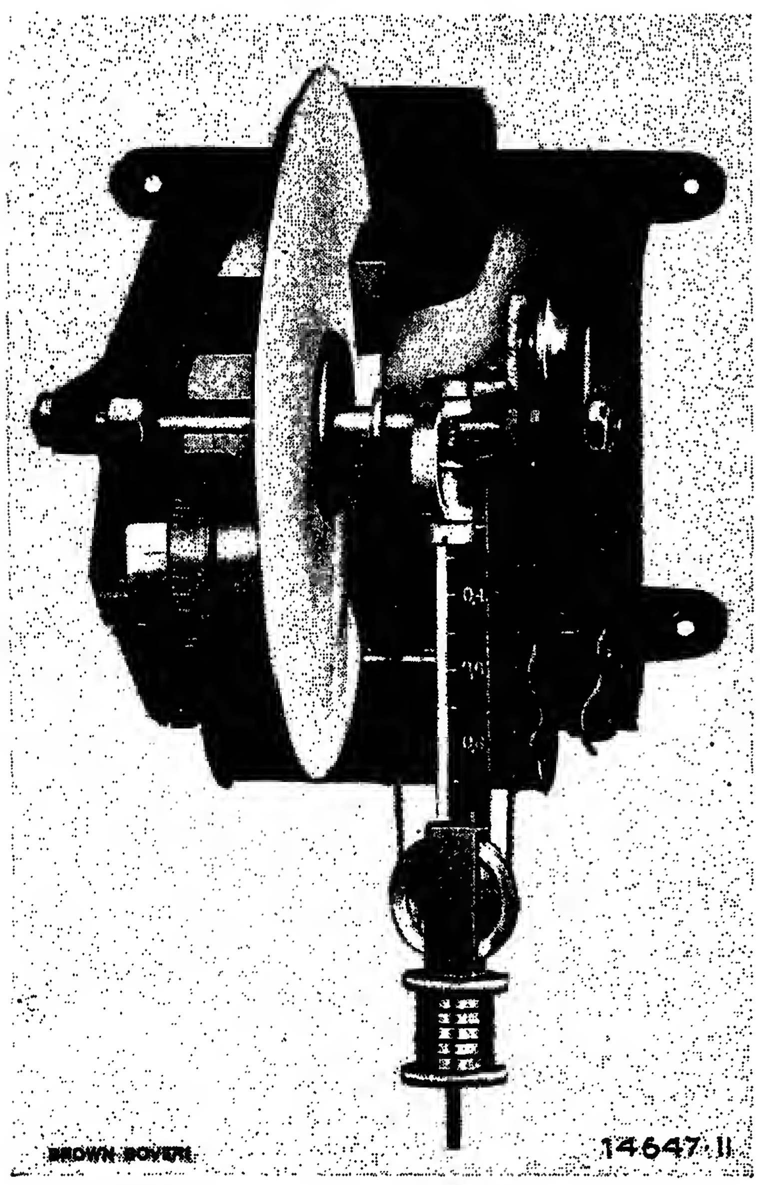


Fig. 21. **Over-current relay, Type A 2 (without casing).**

Over-current relay Type A 2, known as the aluminium-disc relay, was invented and produced by Brown, Boveri & Co. more than 20 years ago. It is based on the Ferraris induction principle and is the forerunner of all the similar relay types built by numerous firms, none of which, however, can compare with it from the point of view of simplicity.

The principal parts of the relay are the magnet with the aluminium disc and counter-weight, the current coil, and the contacts.

The magnet is a laminated iron core between the poles of which an aluminium disc is pivoted. Short-circuited rings are placed round half the surface of each pole and, when the magnet is sufficiently energised, they produce a magnetic field which lags behind that produced by the main coil and, with it, create a rotating field which causes the disc to revolve. One of the pole shoes can be rotated and bears a scale of degrees. When this rotary pole is set in position 0°, the short-circuited rings are symmetrical, and their effect cumulative as regards the torque exercised on the disc. When the pole is set in position 180°, the short-circuited coils oppose each other, and no torque is

exercised on the disc. Thus, by adjusting the setting of the rotary pole, a big range of adjustment is obtainable for the pick-up current.

The torque of the disc is opposed by a counter-weight suspended by a small pulley wheel from a thread, one end of which is secured to a small drum on the disc spindle, and the other to an adjustable time-setting drum on the frame. The more thread wound on the time-setting drum, the fewer the number of disc revolutions required to bring the counter-weight to its top position, where it makes or breaks a contact. In order to prevent the thread from being unduly strained when the torque on the disc is excessive (during a short circuit for example), the disc is not rigidly mounted on the spindle but is secured by a slip coupling, so that it can continue to revolve, despite the fact that the spindle has been stopped by the counter-weight. A steel magnet is also provided, between the poles of which the disc revolves. The resulting eddy currents in the disc cause the speed to increase gradually when the current grows stronger and to tend towards an asymptotic value.

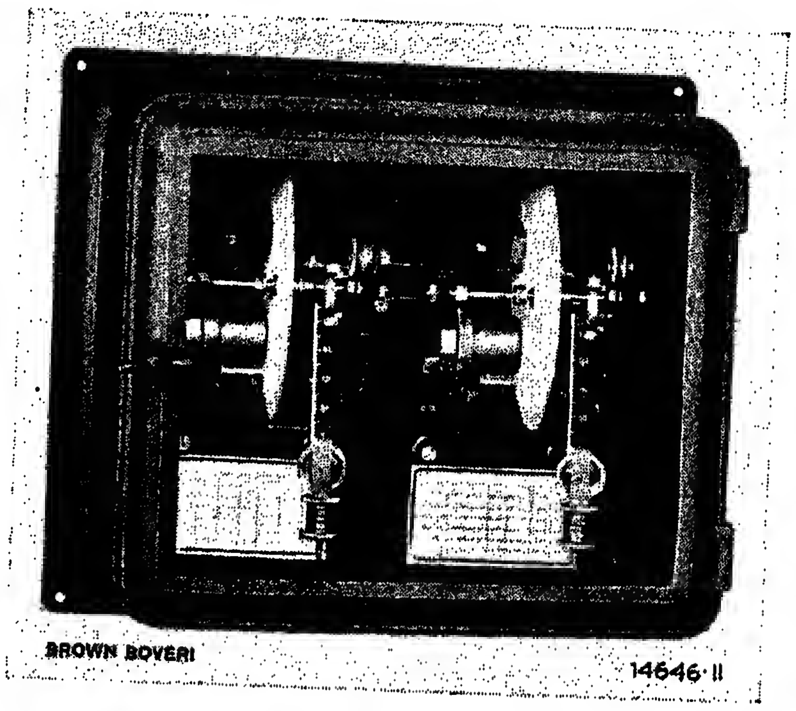


Fig. 22. **Over-current relay, Type A 2/2, raised-type casing.**

When an excess current occurs strong enough to create a torque in the disc which can overcome the pull of the counter-weight, the disc begins to revolve, winding up the thread and the weight, and the stronger the excess current the faster the speed of the disc. On reaching its limiting position, the counter-weight strikes the contact spring and thus operates the contact.

When tripping has been effected, the counter-weight causes the disc to revolve in the opposite sense, unwinding the thread. This also happens if, while the relay is acting, the current should decrease before the counter-weight has reached its top position.

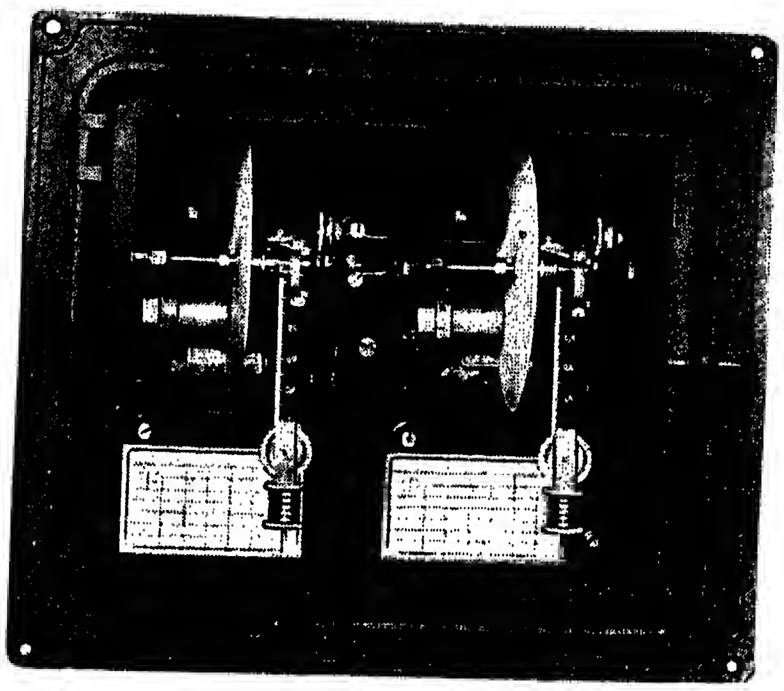


Fig. 23. **Over-current relay, Type A 2/2, flush-type casing.**

Over-current relay A 2 is built either in a raised or flush casing designed to hold, one, two, or three relays. These relays can only be mounted vertically.

The pick-up current of the relay can be set within a range of one to three times the rated current, by altering the position of the rotary pole. The time-limit varies according to the strength of the current and the travel of the counter-weight. For a given current setting and a given travel, the time limit varies inversely as the strength of the excess current. With short circuits of from twice to four times the rated current, the inverse ratio of the time limit to the strength of the excess current disappears and the time limit becomes constant, although it can still be adjusted by varying the travel of the counter-weight. Fig. 24 gives graphically the pick-up currents of the relay and the corresponding time limits, for different settings of the rotary pole and for the maximum travel of the counter-weight (72 mm). Fig. 25 gives the curves for the same setting of the rotary pole (120°) but for different counter-weight travels.

A calibration table is supplied with each relay on which are given the time limits for different currents with different rotary-pole settings and the maximum counter-weight travel.

The contacts of the relay are either of the closing or opening type and their design is shown in Fig. 26. The relay can be used for all the usual tripping methods. With direct current abt. 100 watts, and with alternating current 300 VA tripping power should not be exceeded.

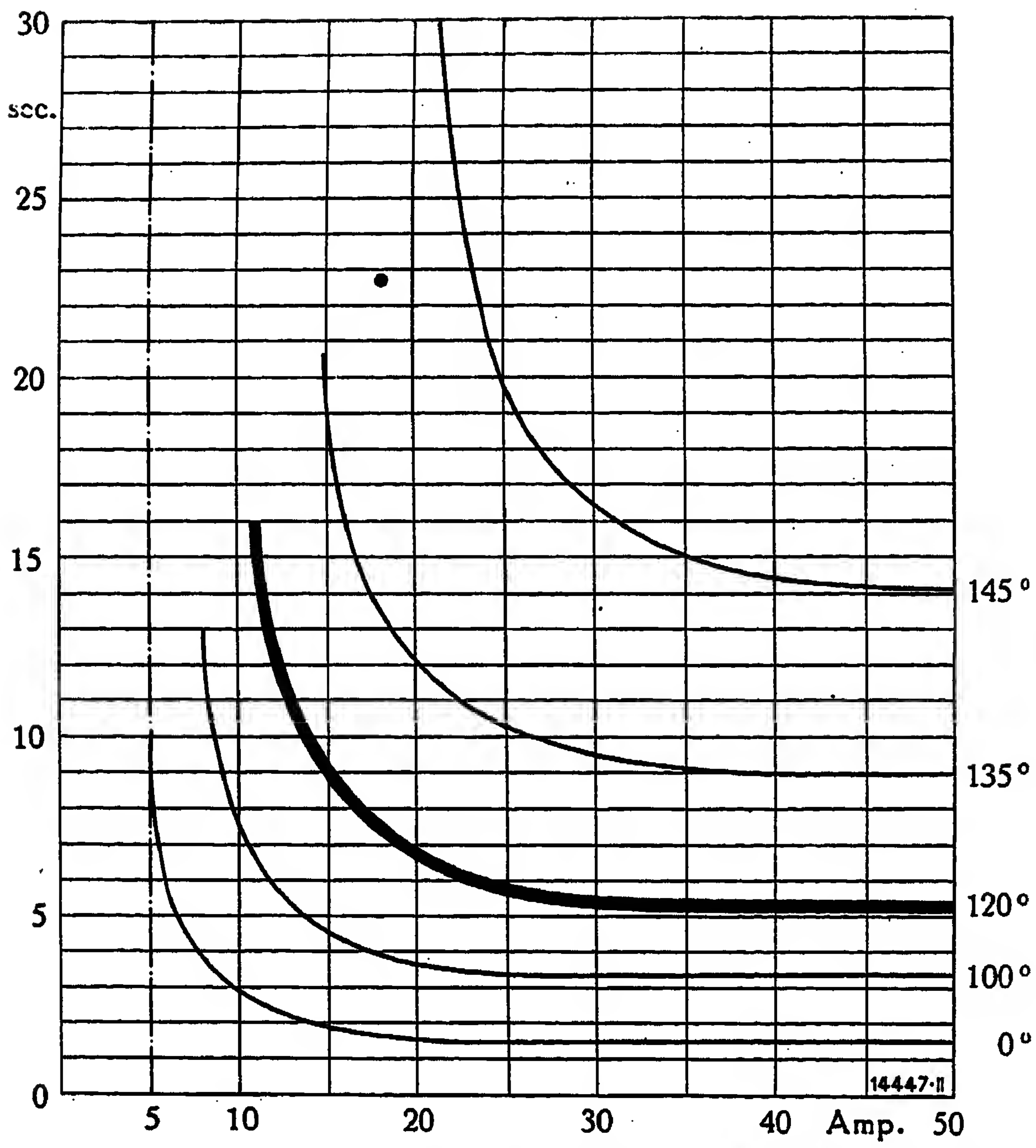


Fig. 24. **Variation of the time limit with the current for different positions of the rotary pole, at 50 cycles and maximum travel of counter-weight.**

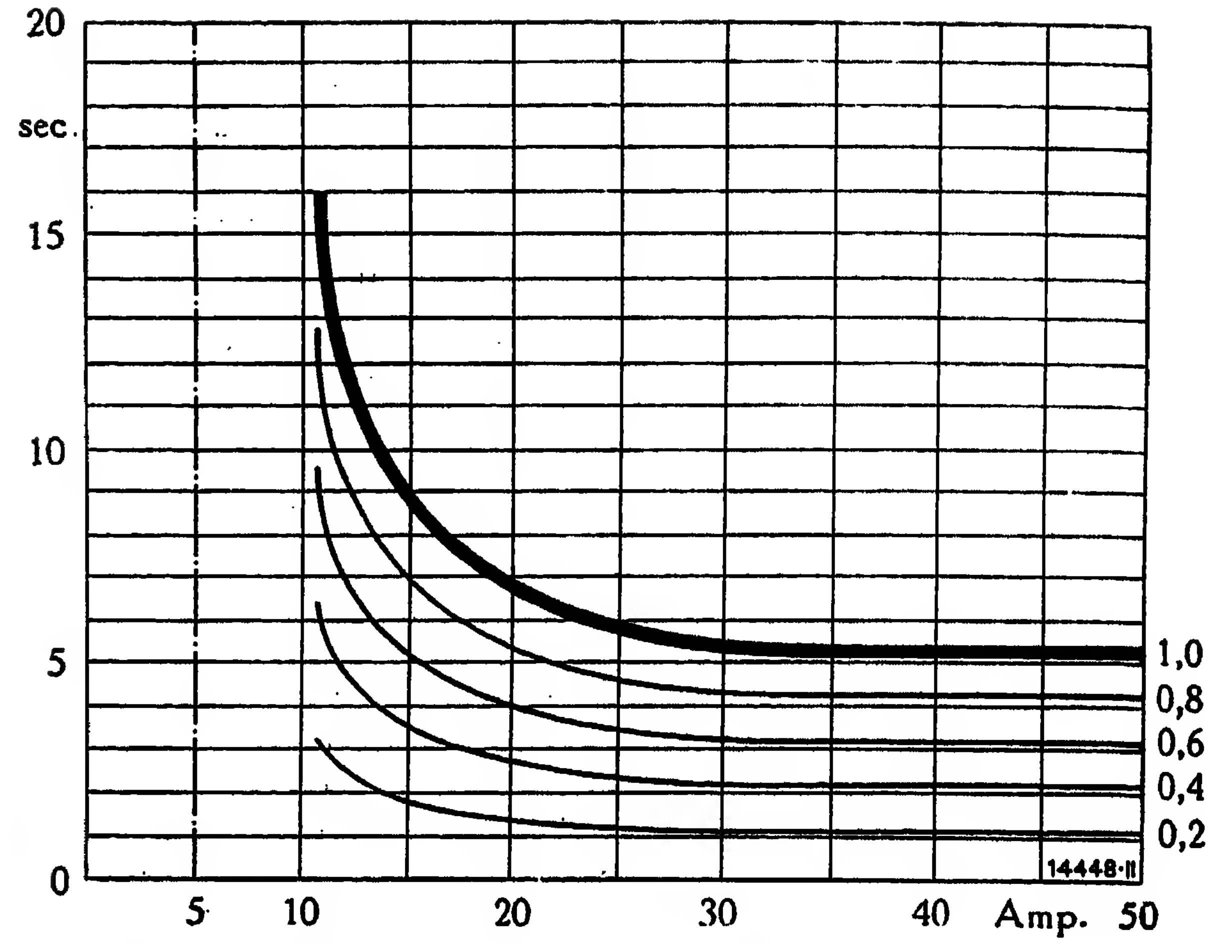


Fig. 25. **Variation of the time limit with the current for different travels of counter-weight; rotary pole set at 120°, frequency 50 cycles.**

Over-current relay A 2 can be used in all plants where, for some reason, definite time-limit relays are not desirable.

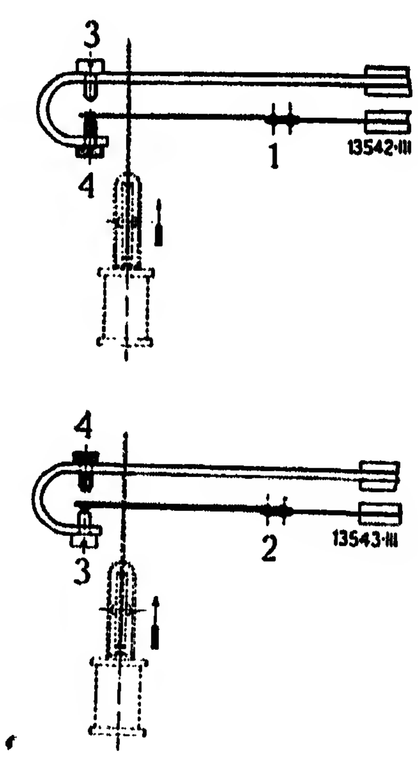


Fig. 26.
Above: closing contact,
Below: opening contact.

1 and 2. Contact spring.
3. Screw with platinum tip.
4. Screw with ivory tip.

On a distribution system, it is possible to make only that switch trip which is closest to the point of short circuit, by suitably setting the relays and by appropriately grading the current transformers from which they are supplied. These relays can, therefore, be used to advantage for protecting lines and sections of systems which are fed by different power stations. It is, nevertheless, advisable to ask for special information on the kind of relay to be chosen in cases of this kind.

As already mentioned, this type of relay has been in use for more than 20 years. Many thousand are operating in alternating-current plants of every output and pressure. Owing to continual improvements, based upon the experience of years, this relay is to-day still among the most up-to-date apparatus on the market, and is specially adaptable to selective protection.

OVER-PRESSURE RELAY, TYPE A 2.

Over-pressure relay Type A 2 is an inverse time, secondary relay identical in design to the over-current relay Type A 2 except that the current coil is replaced by a pressure coil. The pressure under which the relay acts can be set within a range of 1·35 to 1·9 times the rated pressure. The time limit depends on the pressure, and, for a given setting, it is the shorter the higher the pressure above the pick-up value. This relay is only supplied for auxiliary-current tripping with closing contacts. Its field of application is the same as that of over-pressure relay Type H 2 and it is also necessary to insert an ohmic resistance in series with the pressure coil when the relay is being used for the demagnetisation of generators, in order to make the apparatus independent of changes in frequency.

REVERSE-POWER RELAY, TYPE B.

Reverse-power relay Type B is a secondary relay with short time limit. Its duty is to actuate an alarm device or to trip a switch, when the sense of energy flow is reversed.

The principal parts of the relay are the magnets with aluminum disc and counter-weight, the coils, and the contacts.

The magnets have laminated iron cores. A coil is fitted on each of the two magnets. In the case of three-phase current, one of these coils is connected to the line pressure over a series resistance and the other is fed by a current transformer, inserted in the current phase perpendicular to this pressure.

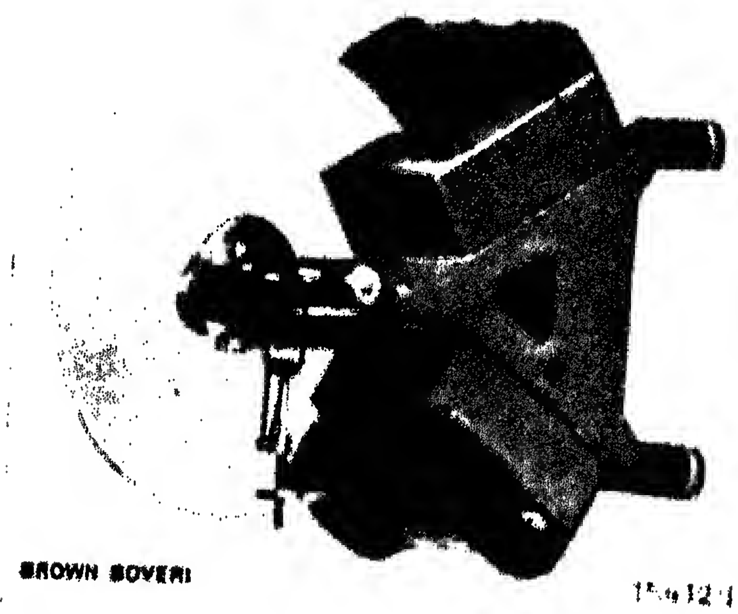


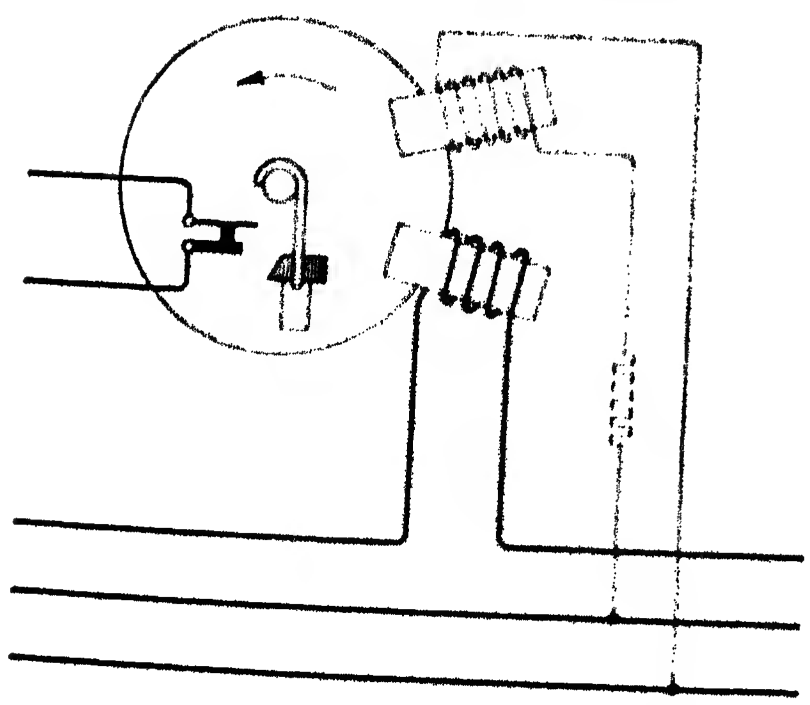
Fig. 27. Reverse-power relay, Type B 2.

An aluminium disc is pivoted between the poles of these two magnets, to the spindle of which the two ends of a thread supporting a counter-weight are fastened.

When energy flows in the "forward" sense, the aluminium disc revolves in that sense which causes the counter-weight to be wound up until its movement is arrested by a fixed stop. When energy flows in the "reverse" sense, the disc revolves in the opposite direction and the counter-weight is wound up and carried past the stop till it actuates the contacts.

The contacts are designed as in over-current relay Type A 2. After tripping has been effected, the disc revolves back again under the action of the counter-weight.

The reverse-power relays are delivered with raised or flush-type cases built to hold one, two, or three relays. The relays can only be fitted vertically.



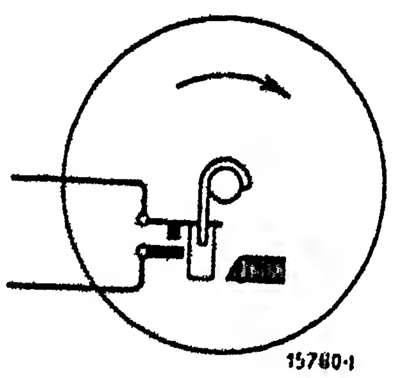


Fig. 28. Reverse-power relay with three-phase connection.

The reverse-power relay acts under full service pressure as soon as the reverse current flow has attained about 10 % of the rated current for all power factors between 0·4 and 1. The acting of the relay is thus pratically

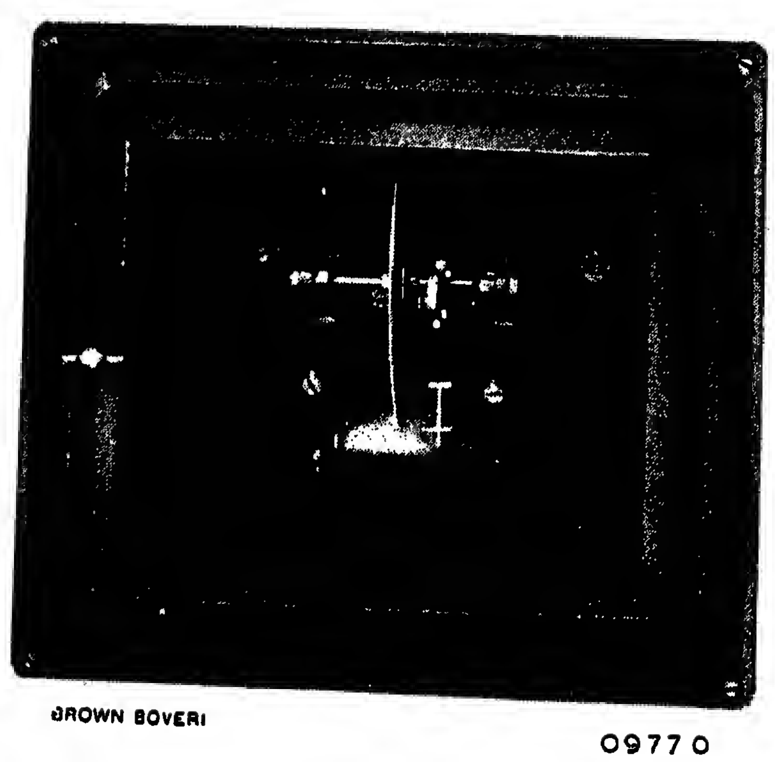


Fig. 29. Reverse-power relay, Type B 2/1, with flush-type casing.

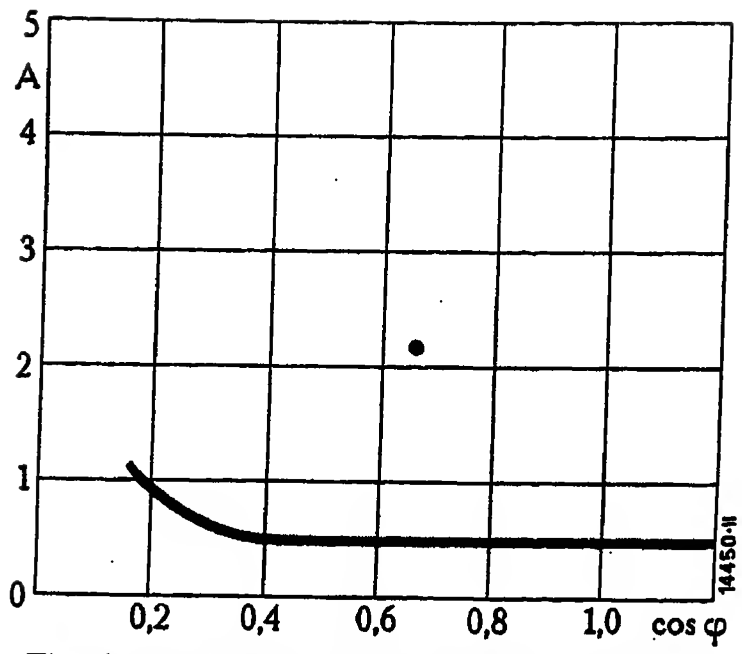


Fig. 30. Variation of the pick-up current with the phase displacement under full pressure.

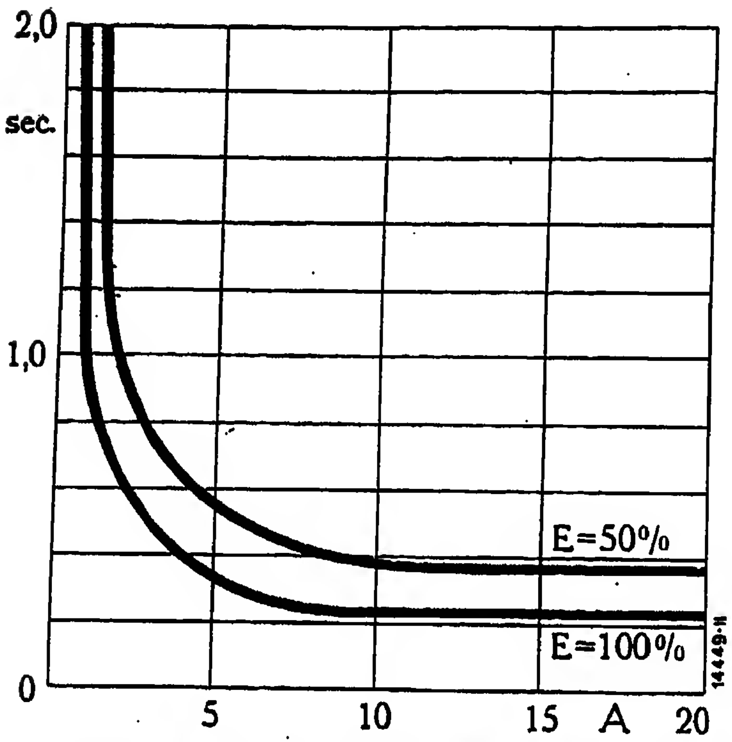


Fig. 31. Variation of the time limit with the current at a frequency of 50 cycles and for full travel of counter-weight.

independent of the phase displacement. When the strength of the current is three or more times the rated current (short-circuit), the relay will act even if the pressure has dropped to only a fraction of the normal pressure, because, with single-phase short circuits, which are the most common, there is always sufficient pressure remaining to make the disc revolve.

The mean travel of the counter-weight is 20 mm. By fastening the adjusting clamp of the counter-weight higher or lower the travel can be varied between the limits of 5 and 40 mm, the time limit being thus proportionately altered. Fig. 31 shows graphically how the time limit varies with the current for full rated pressure (E=100 %) and for half pressure (E=50 %).

Reverse-power relays are only built for 50 and 40 cycles and only for auxiliary current tripping. With closing or opening contacts for direct current, about 100 watts tripping power must not be exceeded, or 300 VA with alternating current.

The relay is very useful for cutting out and demagnetising damaged generators, together with the transformers to which they may be connected. The reverse effect takes place even with a short circuit between coils and not, as with differential current protection, only after earthing has occurred.

The reverse-power relay is also used for the selective protection of distribution systems, either alone, or in conjunction with over-current relays. Under these circumstances, it acts so that only that switch is tripped which isolates the defective section from the source of supply while all the other switches remain closed. The following figures show this arrangement for a branching station with energy flow in one sense only and with energy flow in both senses.

(a) *Branching station with energy flow in one sense.* As shown in Fig. 32, the incoming lines I and II (which can either be parallel lines from the same station or separate lines from two stations) are protected by reverse-power relays while the outgoing feeder III to the consumer is only equipped with an over-current relay. All the relay contacts are open for normal service conditions, as shown. In case of a short circuit on one of the lines I or II, the reverse flow of energy from the unaffected line over the branching station, makes the reverse-power relay act. This causes the defective section to be cut out practically instantaneously. If a short circuit occurs in the outgoing feeder III the over-current relays of that line alone can act, while the flow of energy to the branching station along lines I and II continues, for supplying whatever other outgoing feeders there may be.

(b) *Branching station with fluctuating sense of energy flow.* Lines which connect up, directly or indirectly, two generating stations are always subject to a reversal of energy flow either under normal service conditions, or exceptionally if a defect arises.

The switches of such lines must, therefore, be equipped with reverse-power relays (directional or blocking relays) as in Fig. 33, in addition to over-current relays (inverse or definite time-limit relays). The reverse-power relays do not themselves operate the tripping gear of the switches but only lock or free them. In line I, in which the energy is assumed to be flowing in the sense of the arrows, the tripping gear is interlocked because the contacts of the reverse-power relay are open. In lines II and III, in which the flow of energy is outwards, the contacts of the reverse-

power relay being closed, hold the tripping gear in readiness to act when required. In case of a short circuit in line I, for example, the sense of energy flow of lines II and III is momentarily changed and sets towards I. The discs of the reverse-power relays immediately revolve in the opposite sense, thus interlocking the switch-tripping gears in lines II and III (now incoming lines)

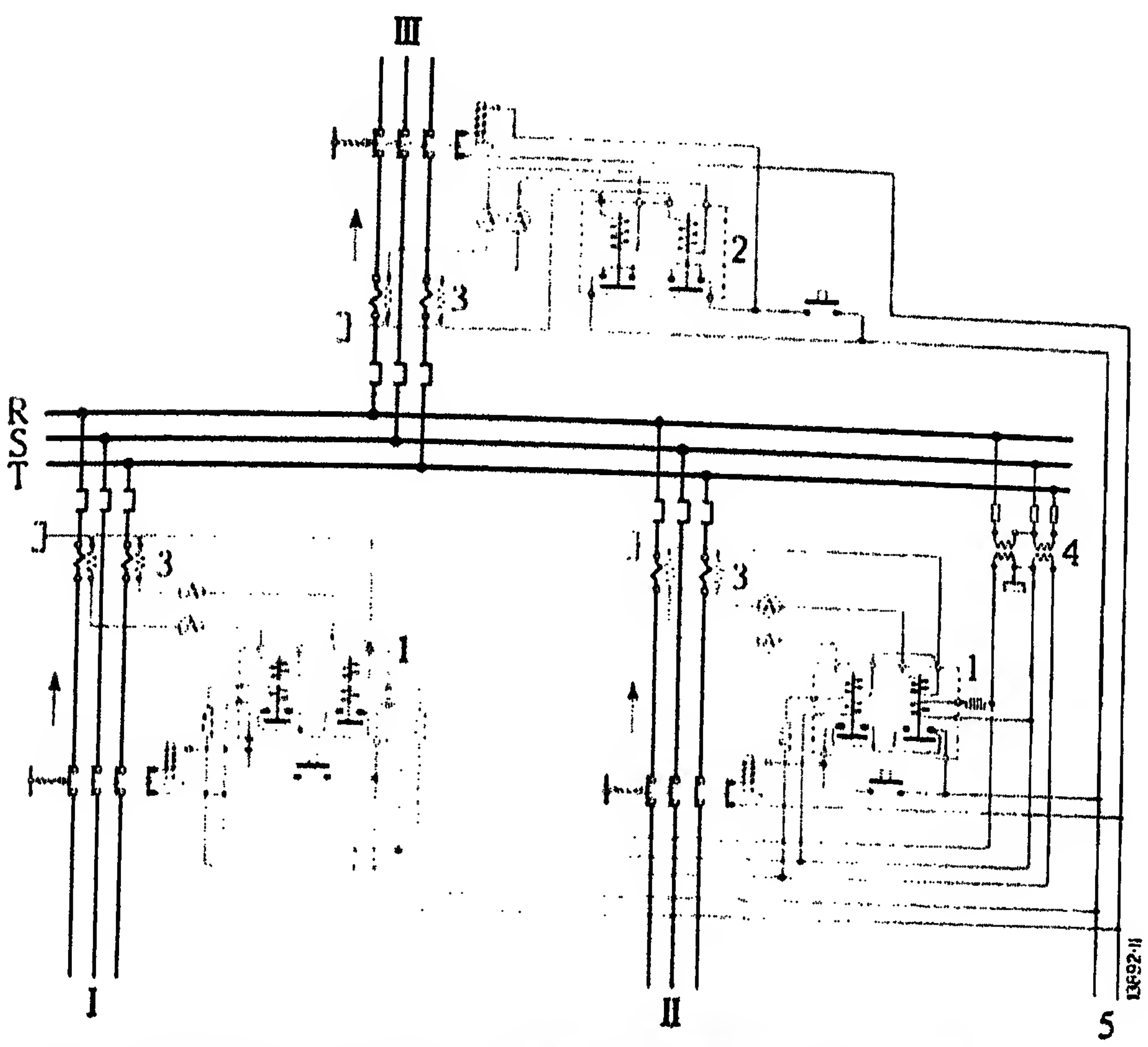


Fig. 32. **Diagram of connections for the selective protection of a branching station with energy flow in one direction only.**
1. Reverse-power relay. 2. Over-current relay. 3. Current transformers. 4. Pressure transformers. 5. To the supply of auxiliary current.

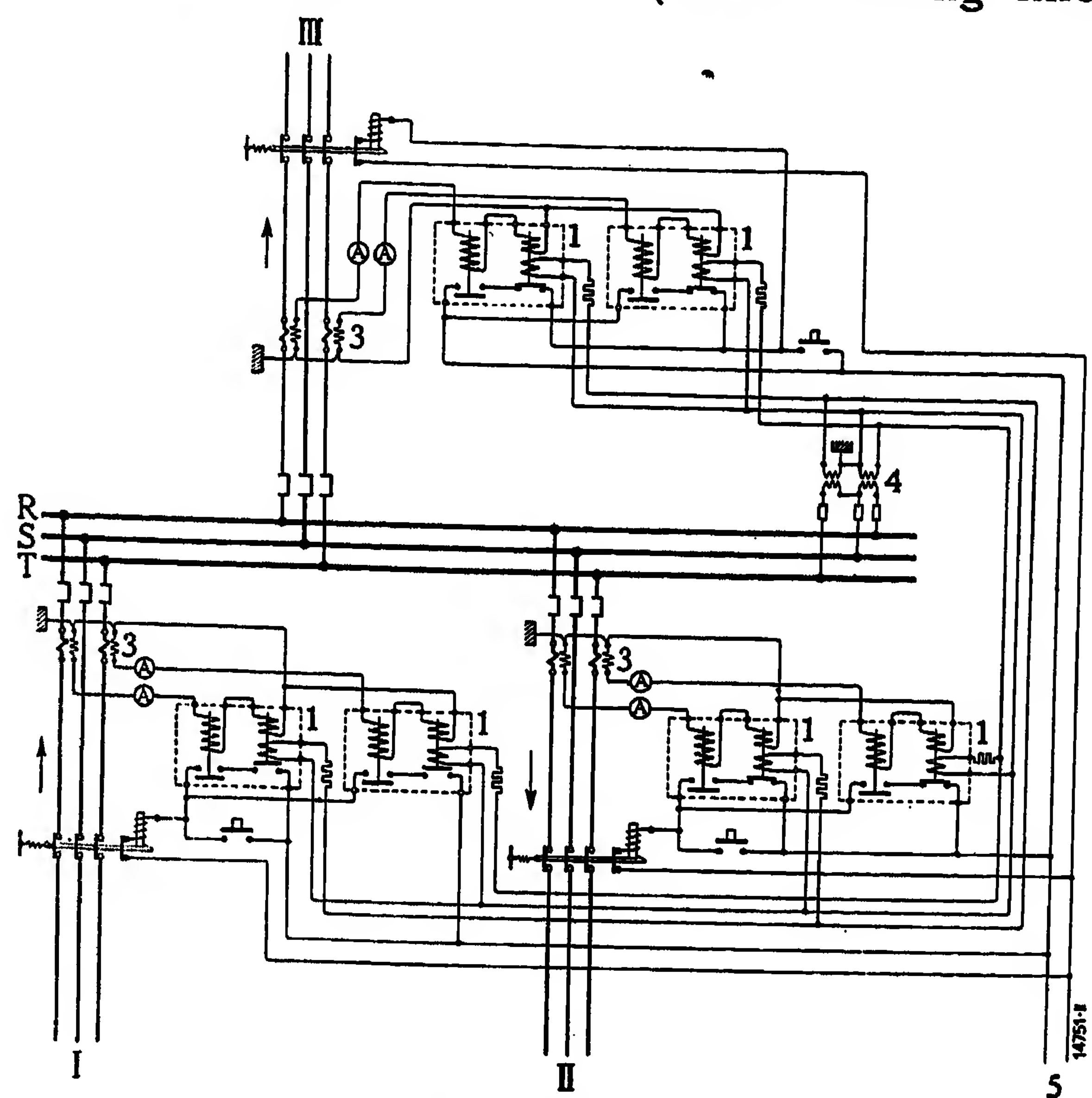
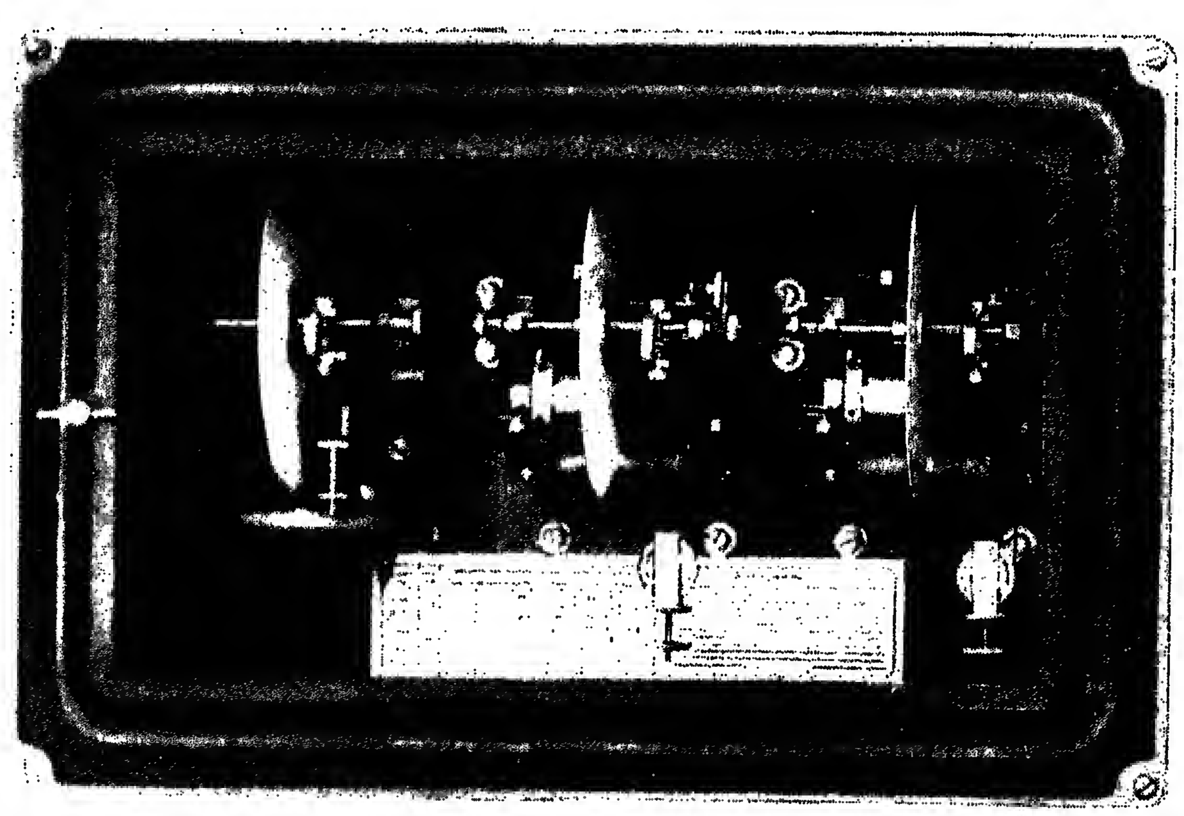


Fig. 33. **Diagram of connections for the selective protection of a switching station with fluctuating direction of energy flow.**
1. Over-current and reverse-power relays. 3. Current transformers. 4. Pressure transformers. 5. To the source of auxiliary current.

and releasing for action the tripping gear of line I. The trip is effected as soon as the time limit of the over-current relays has run out. By a suitable grading of the time-limits of the over-current relays from station to station it is possible to make sure that only that switch which cuts off the damaged section from the interconnecting switching station is tripped, on whatever line a short circuit occurs.

COMBINED RELAYS.

The different relays described can be combined in any manner desired and mounted in a common casing. As many as three relays can be thus mounted together, the same casings being used as for over-current relay Type A 2.



BROWN BOVERI 09771

Fig. 34. **Combined relays.**

RELAYS

FOR THE

PROTECTION OF DISTRIBUTION SYSTEMS

BROWN, BOVERI & COMPANY
LIMITED
BADEN (SWITZERLAND)

790 E

April, 1924

CONTENTS

RELAYS

FOR THE PROTECTION OF DISTRIBUTION SYSTEMS.

Decimal index 621. 319. 8.

I. INTRODUCTION.

THE rapid increase in the demand for electrical energy compelled power companies to lay down complicated distribution systems interconnected at many points. Local disturbances, such as short-circuits, naturally have a very far-reaching effect on such systems and are liable to influence considerable areas.

As it proved impossible to do away altogether with these disturbances, which occasion loss of time and money, means were sought by which their results could be reduced, or restricted in extent as far as possible.

The problem of limiting the short-circuit currents flowing towards the seat of the disturbance, and their effects, was solved with unparalleled success by the introduction of the automatic current-limiting regulator built by Brown, Boveri & Co. As shown in practice, not only does this apparatus reduce the strength and duration of short circuits, thus sparing the oil switches, but, after the switch of the defective section has opened, the generators continue to run in perfect synchronism, service is maintained, and the pressure rises automatically to its full normal value.

During the last two years, many very complicated devices and systems of connection, with the object of limiting the trouble to the defective section by tripping the switches closest to that section, have appeared. They have been described in current technical literature under the title of selective protection systems, but have not been sufficiently tried out in practice.

In wide circles, the erroneous view is held that the cutting-out of a defective section can only be carried out by special selective relays.

The object of the present article is to show how selective protection can be successfully carried out on the most dissimilar distribution systems with the aid of the well-known Brown Boveri relay, the simplicity of which has been a factor in its success.

These relays are described in the following paragraphs.

II. OVER-CURRENT INVERSE TIME-LIMIT RELAY, TYPE A 2.

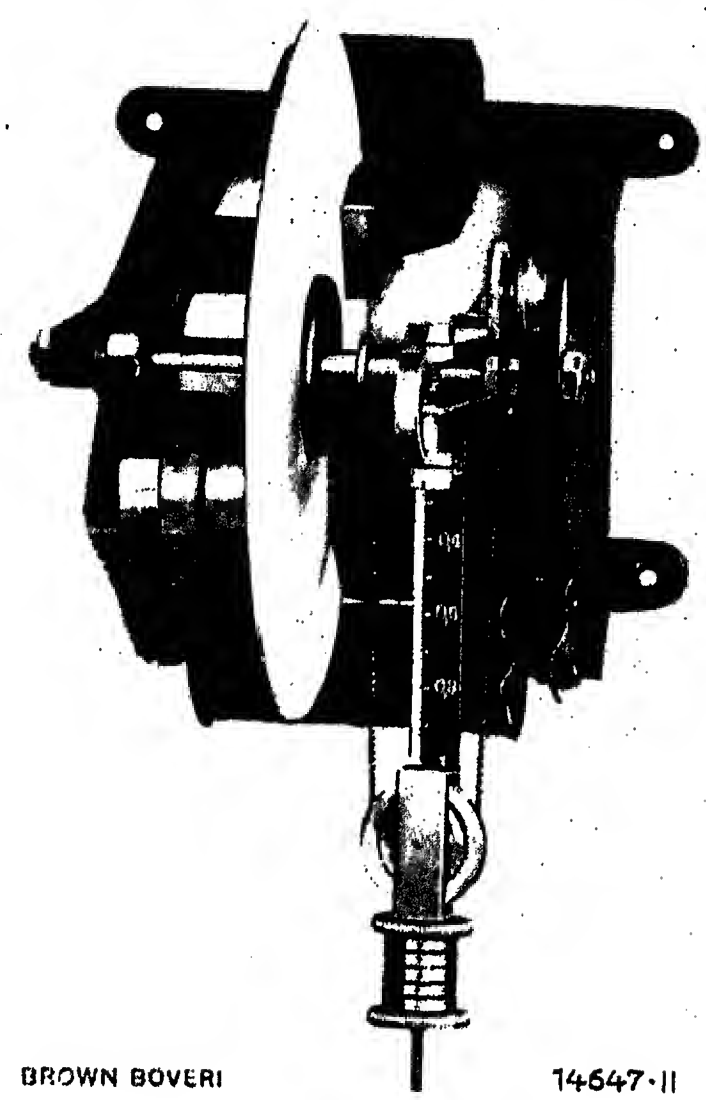


Fig. 1. — Over-current relay Type A 2.

This aluminium-disc relay, the operation of which is based on the Ferraris induction principle, was invented by Brown, Boveri & Co. and has been in use for over 20 years. Its construction is shown in Fig. 1.

An aluminium disc is pivoted between the poles of an electro-magnet connected to a current transformer, and a short-circuited ring surrounds half the surface of each pole, so as to produce a rotating field. One of the short-circuited rings (left-hand in Fig. 1), with its pole shoe, is pivoted in a plane parallel to that of the disc. This adjustable ring carries a scale graduated in degrees and the strength of the torque exercised on the disc depends on its position. In this way, it is possible to set the relay to operate on weak or strong current as required.

The torque of the disc is opposed by a counter-weight suspended on a loop of thread, one end of which is secured to a small rotating drum on the spindle of the disc, while the other end is secured to a second drum attached to the frame. More or less thread can be wound on to the second drum in order to vary the distance through which the counter-weight must be raised, that is to say, the time required to bring the counter-weight to the top position, where it makes or breaks the tripping circuit. In order to prevent

the thread being unduly strained when the torque on the disc becomes excessive (during a short circuit for example), the aluminium disc is not fixed rigidly on the spindle, but transmits its torque through a slip coupling which permits it to continue rotating when the counter-weight has travelled up to its limit position. A steel magnet is also provided, between the poles of which the disc revolves and which produces eddy currents in the latter, damping its motion. The speed of the disc thus increases gradually with the increase of the current and tends asymptotically towards a definite maximum value.

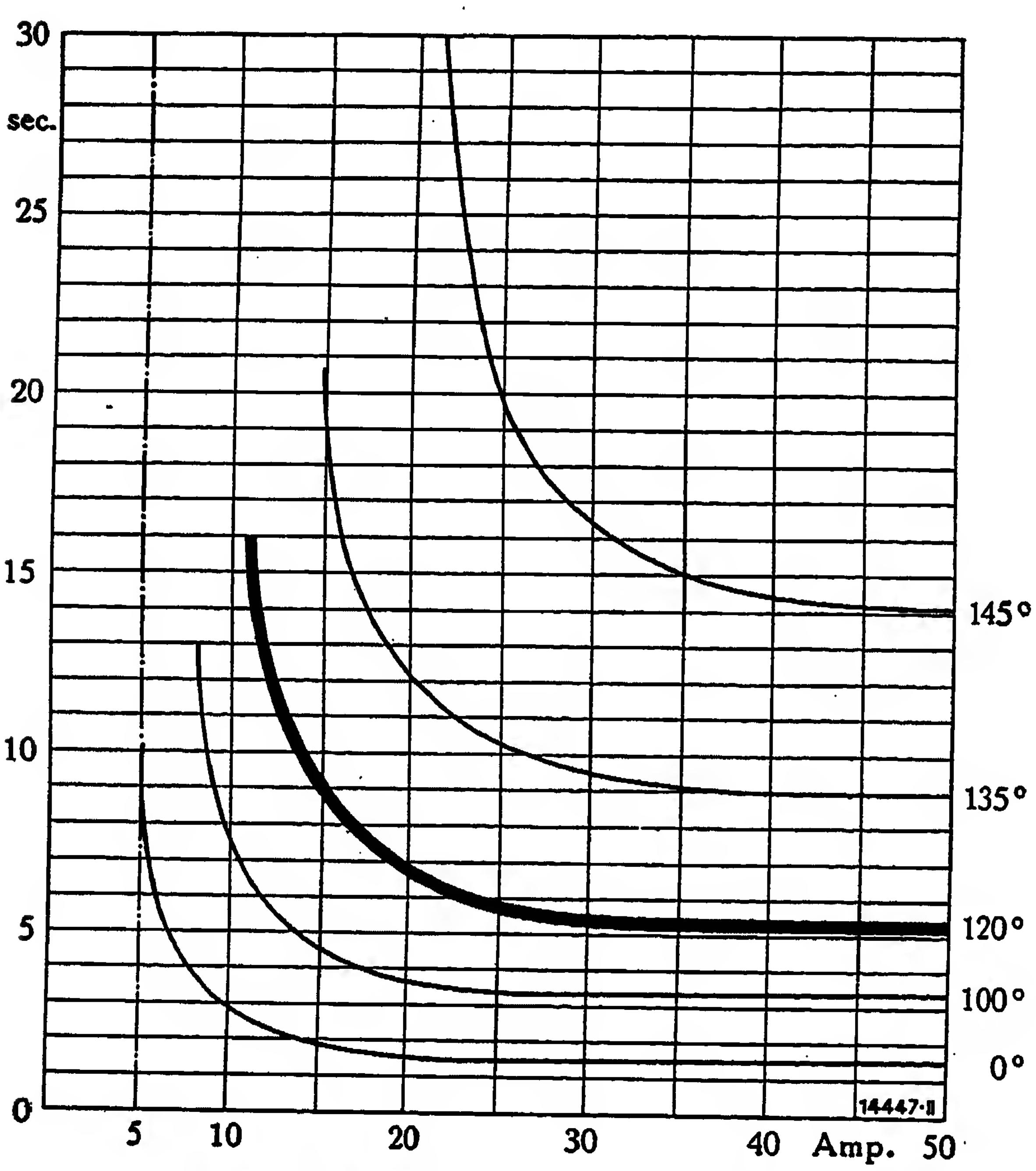


Fig. 2. — Time lag as a function of the current up to 50 A for different positions of the adjustable pole; frequency 50 cycles per second; full travel.

The construction just described and the dimensions chosen for the various parts of the apparatus impart to the relation between the time lag and current strength the characteristics shown in Figs. 2, 3, and 4. The curves indicate clearly how erroneous is the idea, still prevalent in certain quarters, that over-current relays of the A 2 type cause an immediate opening of the switch when a short circuit occurs. It will be seen that, whatever the excess of current may be, there is a perfectly definite minimum time lag for each current setting (i.e. for each position of the pivoted pole). For the longest travel of the counter-weight this lag is of the order

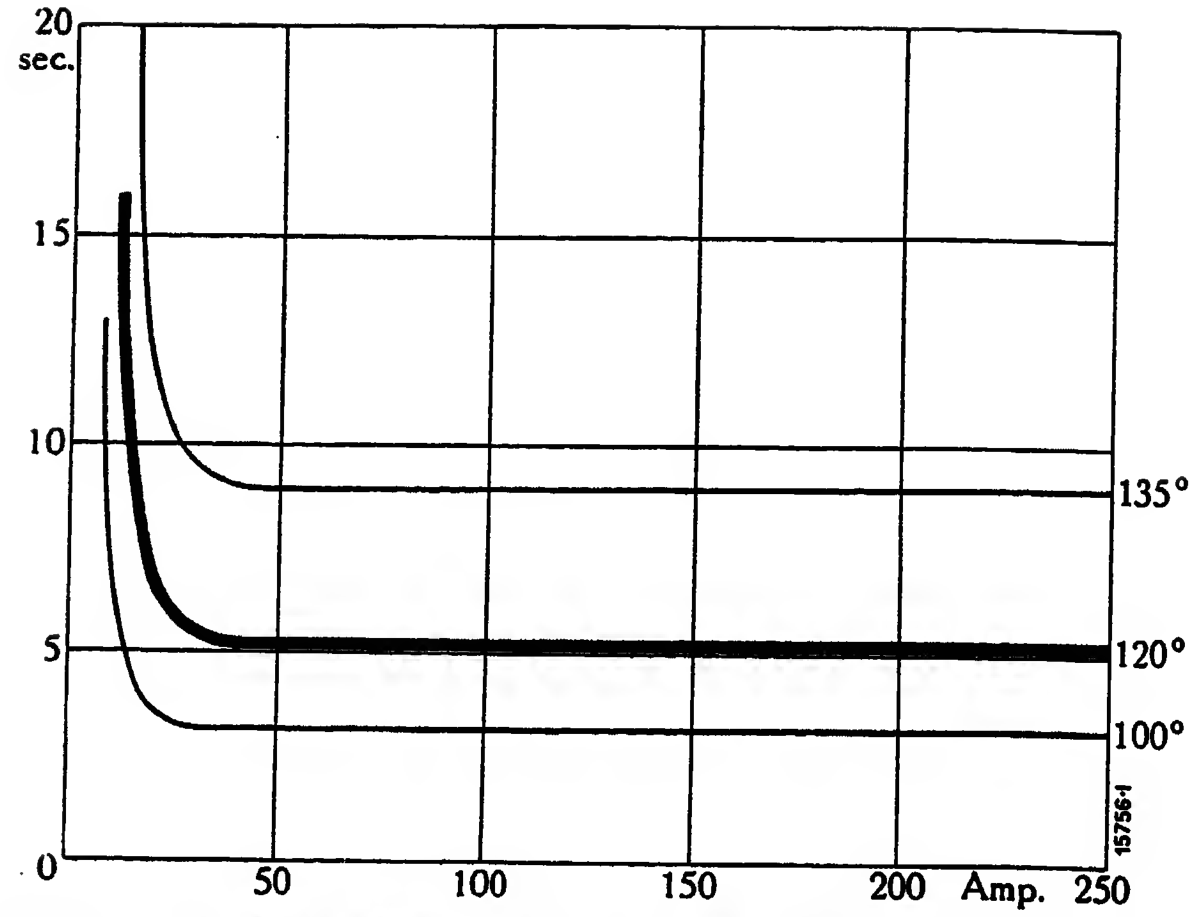


Fig. 3. — Time lag as a function of the current up to 250 A for different positions of the adjustable pole; frequency 50 cycles per second; full travel.

of several seconds, and it decreases approximately in proportion as the travel is shortened (i. e., the shorter the length of the thread). The opinion often expressed, that the aluminium disc over-runs after the short circuit has been cut out, instead of immediately revolving backwards until the normal rest position has been reached, is demonstrated to be quite unjustified by the very careful tests carried out with relays arranged as in Fig. 5. These tests prove that, if the travel of the second relay be lengthened, by two or three millimetres only, a short-circuit current of as much as fifty times the rated current does not suffice to make contact on the second relay, once the current has been cut off by the first relay. This proves that the momentum of the rotating disc is absorbed by the

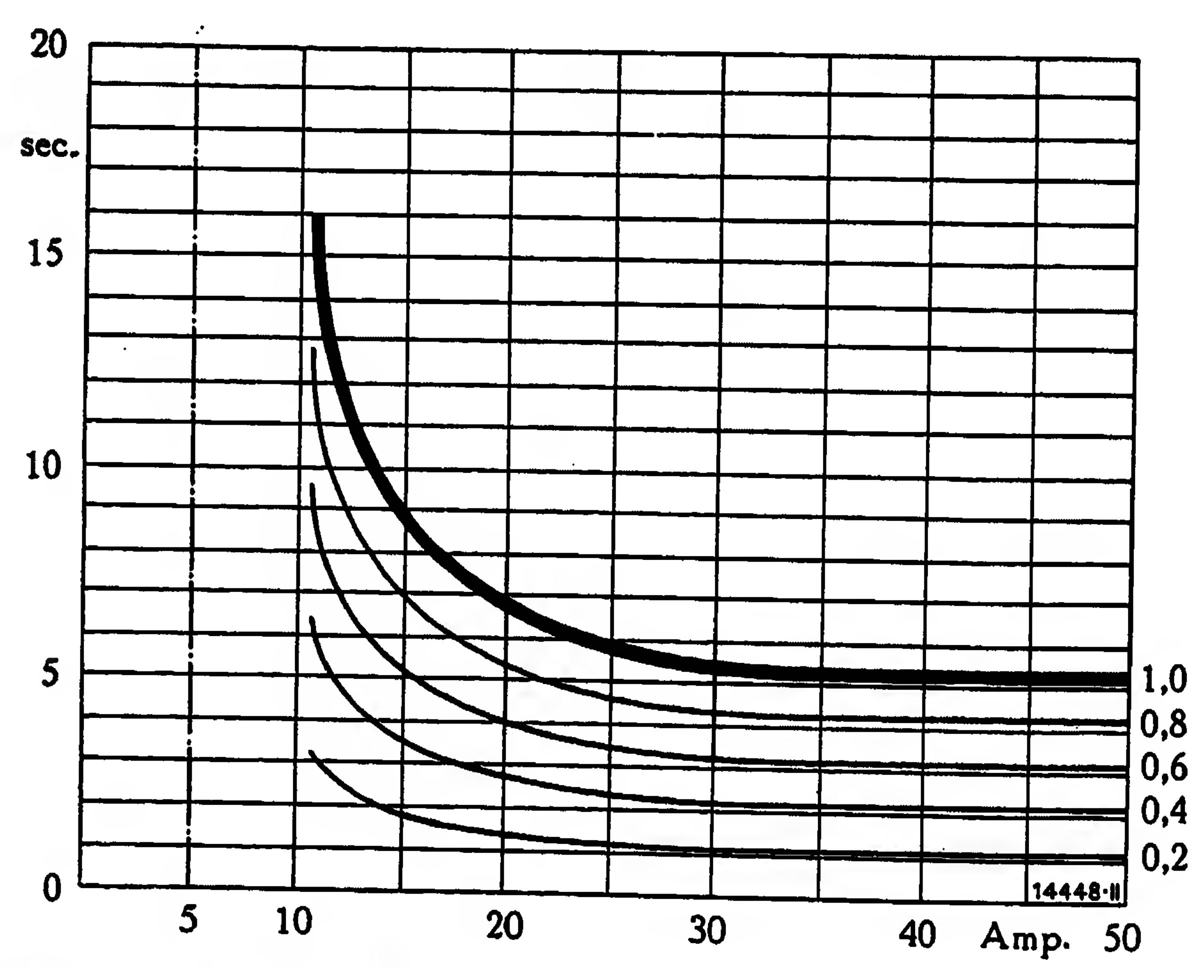


Fig. 4. — Time lag as a function of the current for fractions of the total travel, the adjustable pole being set at 120°; frequency 50 cycles per sec.

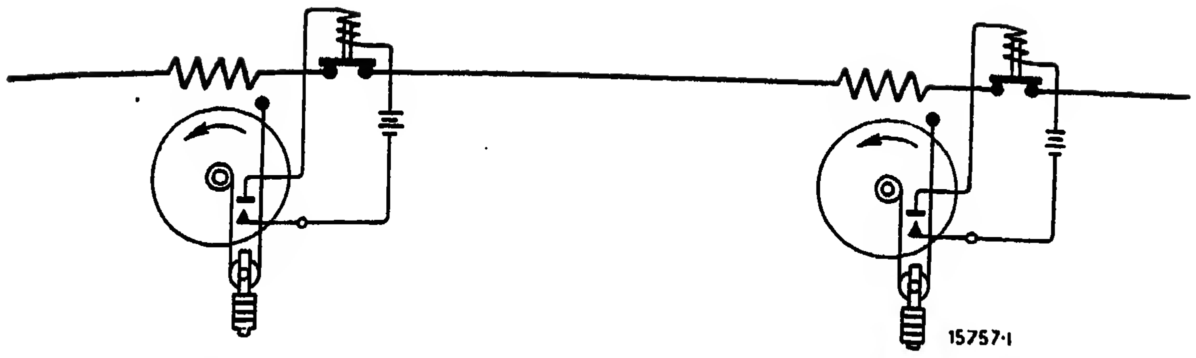


Fig. 5. — Connections for the over-running test.

counter-weight and damping device in less than a quarter of a revolution. Thus the defects inherent to the earlier types of this relay were remedied by the design described, which dates from as early as 1905. Since that time, still further improvements have been effected by adding the travel scale and by changes in the rotating drum. These reduce to a few seconds the undesirably long time lags under slight overloads and increase the setting range to from one to three times the rated current.

On account of the dependence of the time lag upon the current strength, the relay A 2 is in all respects comparable with similar apparatus, described as novelties in current American technical literature and termed "definite minimum time relays". The Brown Boveri over-current relay A 2 can claim the advantage of the simplest design and, consequently, the highest degree of reliability, a quality which has been proved by years of successful operation. These advantages should lead to the rejection of more complicated designs, even should the latter satisfy the requirements of the case in a more complete manner theoretically. The prejudice against an apparently somewhat indefinite time setting is thus practically overcome, and, to-day, the conviction is gaining ground that the inverse characteristic of the relay is, in many cases, an advantage for selective operation. This will be explained in the succeeding paragraphs.

Relays, which momentarily run away under heavy overload or when a short circuit occurs, so that the time-lag curves cut the abscissae axis instead of running parallel to it as shown in Figs. 2, 3, and 4, are useless for selective work. They are better suited to overload protection of individual consumers' installations.

Over-current relay A 2 is very suitable for being built into the control panel of Brown Boveri outdoor oil circuit breakers (Fig. 6), especially on account of the small amount of power it absorbs (about 10 VA at 50 cycles). Although the so-called bushing current transformers of these switches have as primary only the straight conductor, which is equivalent to one turn, they transmit to the relay sufficient energy, even with currents of 70 to 90 amperes, to cause the automatic tripping of the switch. In outdoor control pillars, this operation is generally carried out mechanically, the counter-weight,

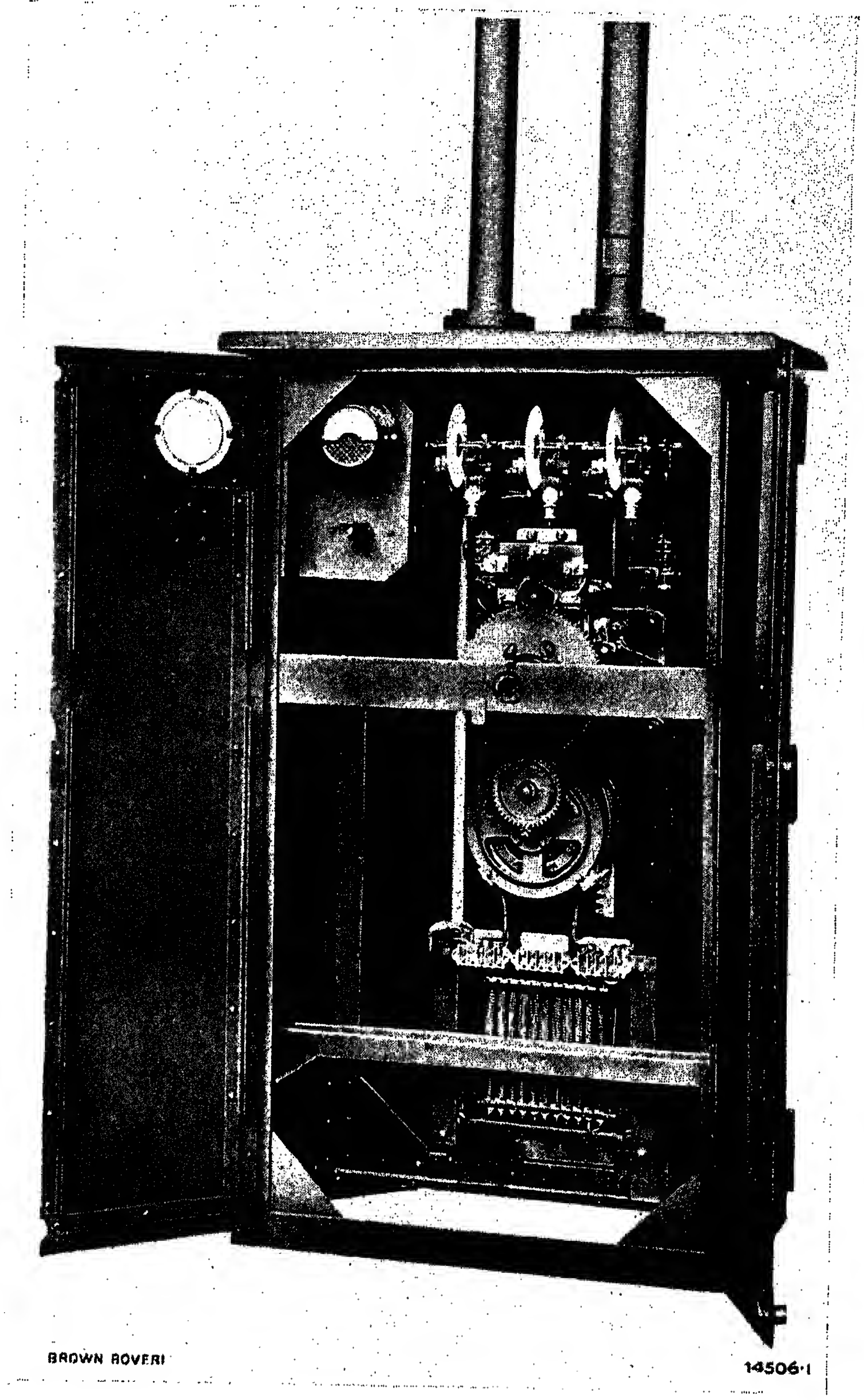


Fig. 6. — Relay Type A 2 built into a control column.

raised by the rotation of the disc, releasing the catch. It can also be effected electrically by a tripping coil and auxiliary source of current, the counter-weight making contact.

III. SERIES DEFINITE TIME-LIMIT RELAY, TYPE H 4.

The series relay constitutes a revival of the principle applied in early plants consisting in the insertion of the tripping coil directly into the high-

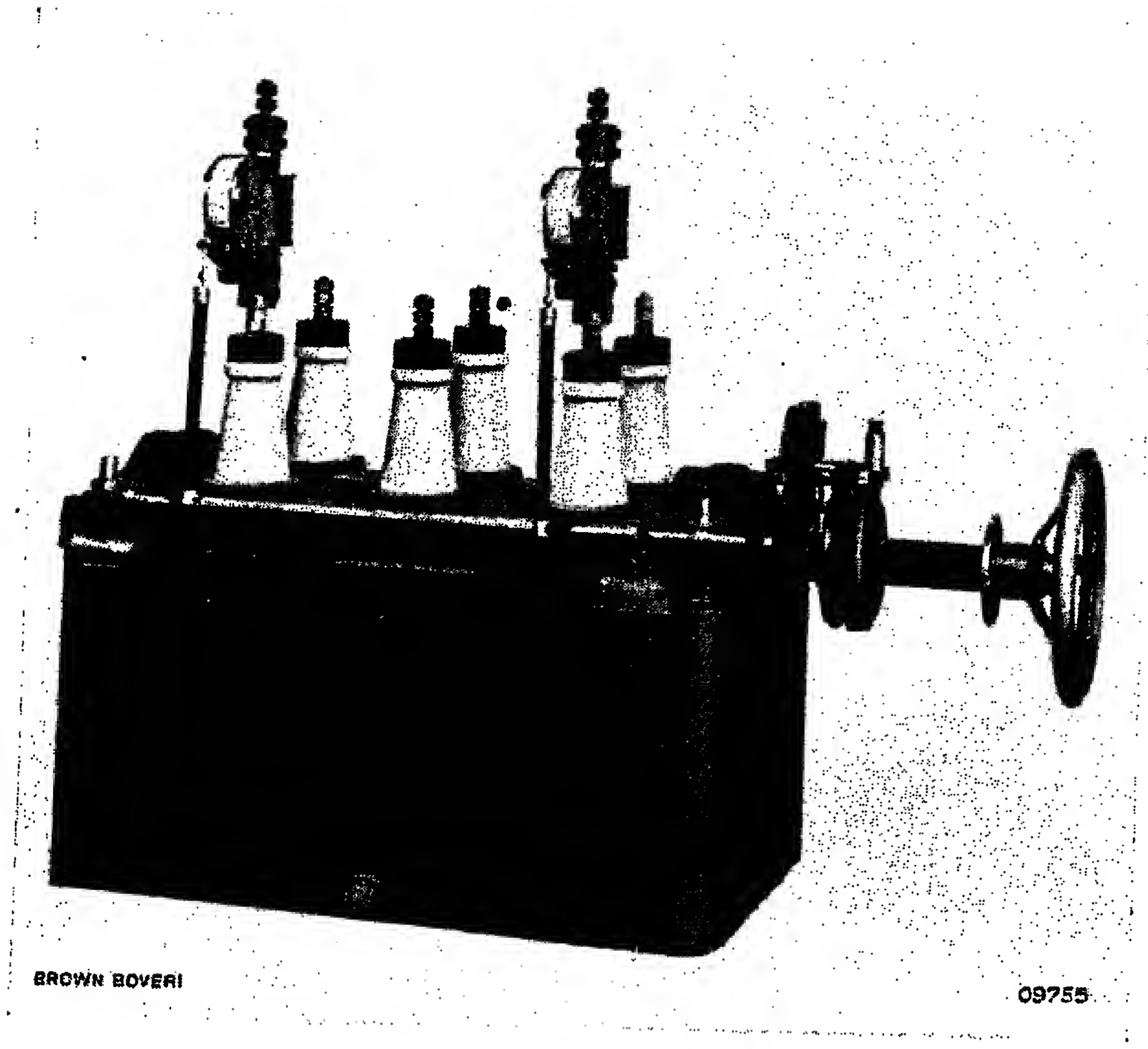


Fig. 7. — Series relays mounted directly on an oil switch.

tension main. It is not, however, simply a trip coil operating instantaneously, such as was used on the early circuit breakers, but a greatly improved apparatus with means for setting the pick-up current and the time lag independently of one another. This relay satisfies the demand for a method of tripping oil switches without current transformers, tripping solenoids, or auxiliary sources of current. The whole mechanism is under high tension, and the armature movement is transmitted to the releasing device through an insulating rod (Fig. 7).

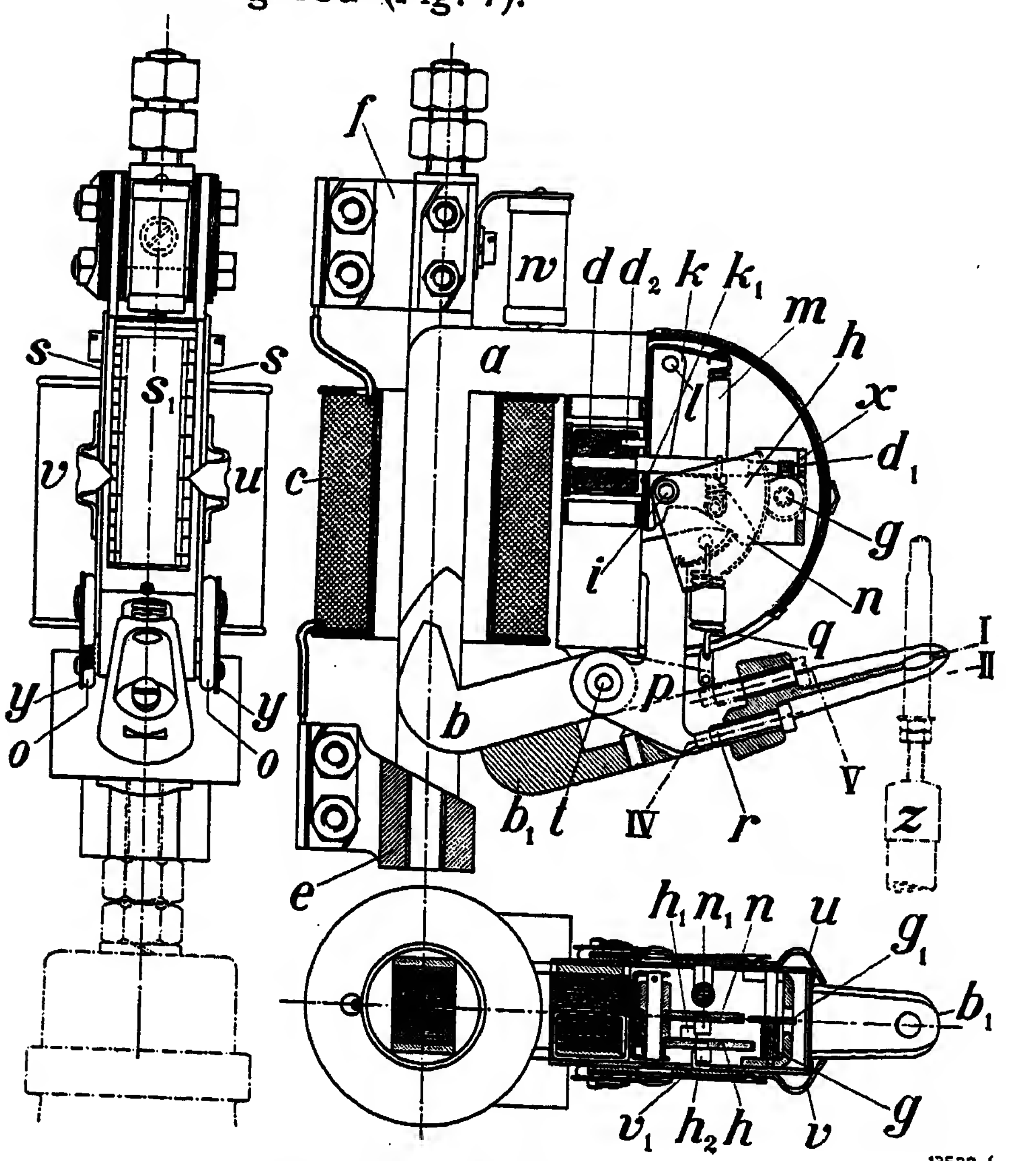


Fig. 8. — Series relay Type H 4.

When the iron core a of the magnet (Fig. 11) is sufficiently magnetised by the current coil c, the armature b is attracted, overcoming the force of the current spring m, and the tripping lever b_1 is carried from position I to II and held there. At the same time, a small squirrel-cage rotor d, mounted in a recess of the iron core, is released and begins to revolve under the influence of the rotating field produced by placing massive short-circuited rings round two diagonally opposite portions of the pole piece. The movement of the small rotor is imparted to a toothed segment h, through the worm d on the motor spindle and the pinion g. This segment travels through a certain arc which can be altered by the time-setting pointer v, and finally it releases the catch which is holding the tripping lever b_1 in position II.

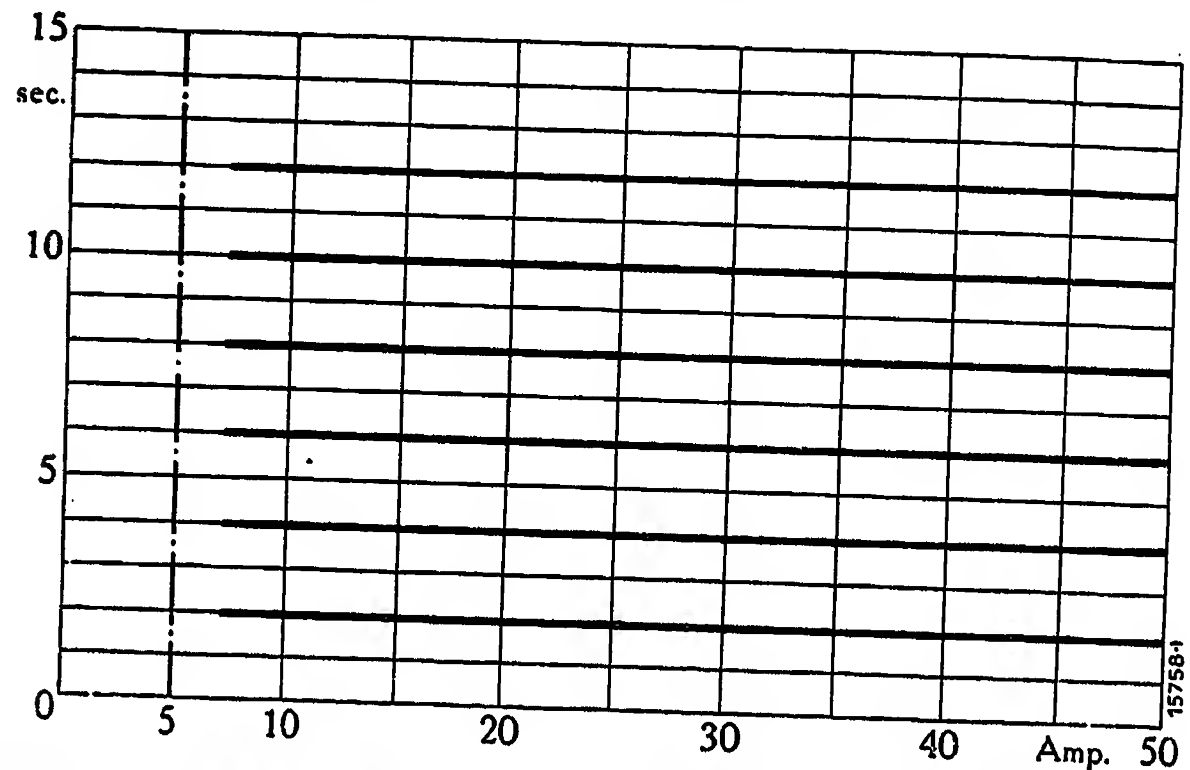


Fig. 9. — Current as a function of time lag for a series relay set for time-limit tripping.

This lever, on being freed, moves with the tripping rod z to the end position and trips the switch. The high saturation of the iron core imparts constant speed to the rotor, whatever the current flowing through the coil. Thus the condition, so often laid down, that the time lag should be the same for all currents, is realised (see Fig. 9).

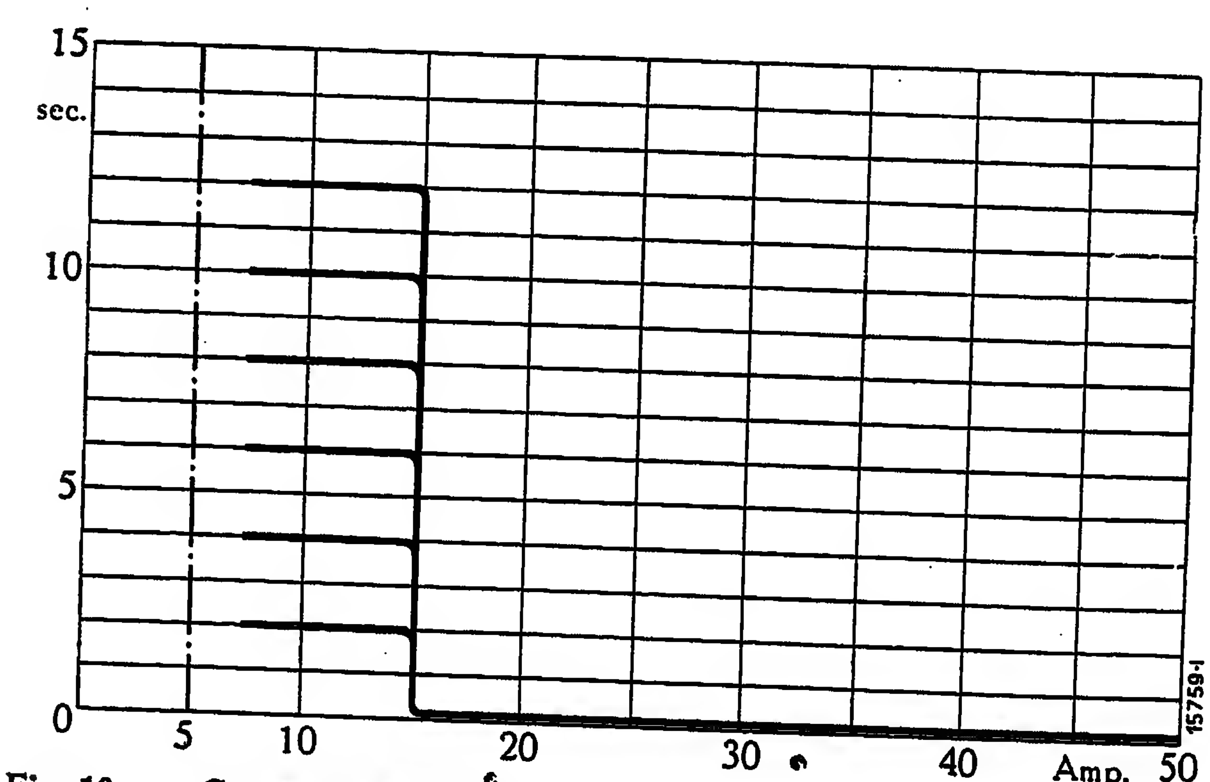


Fig. 10. — Current as a function of time lag for a series relay set for instantaneous tripping.

The pick-up current can be set by adjusting the current spring by the pointer u to any desired value from 1·4 times to twice the rated current. If the screw r be moved from position IV to the upper hole V, the restriction on the tripping lever b_1 in position II is removed, when once the current exceeds three times normal. The relay then acts instantaneously if a short circuit of over three times the rated current occurs, as is shown in Fig. 10.

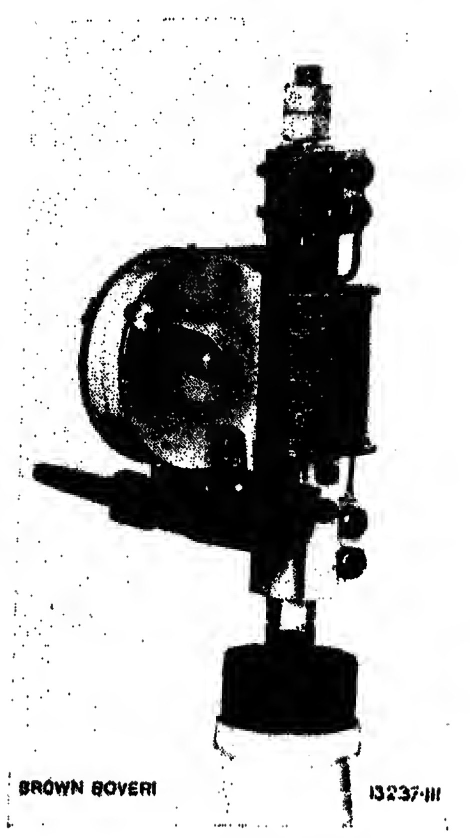


Fig. 11. — Series relay Type H 4.

The flat shape of the series relay allows of building it directly on to the switch insulators without unduly reducing the distance between the poles. The current for which the apparatus operates and the time lag can easily be set, when the apparatus is under pressure, by means of an insulated rod. Thanks to recently introduced designs, even the severest short circuits have no apparent effect on the mechanism.

Further, the position of the screw r, in either the upper or lower hole, as seen from the front, allows of ascertaining if the relay be set for instantaneous operation under a current of more than 3 times normal or for time-limit operation under all conditions.

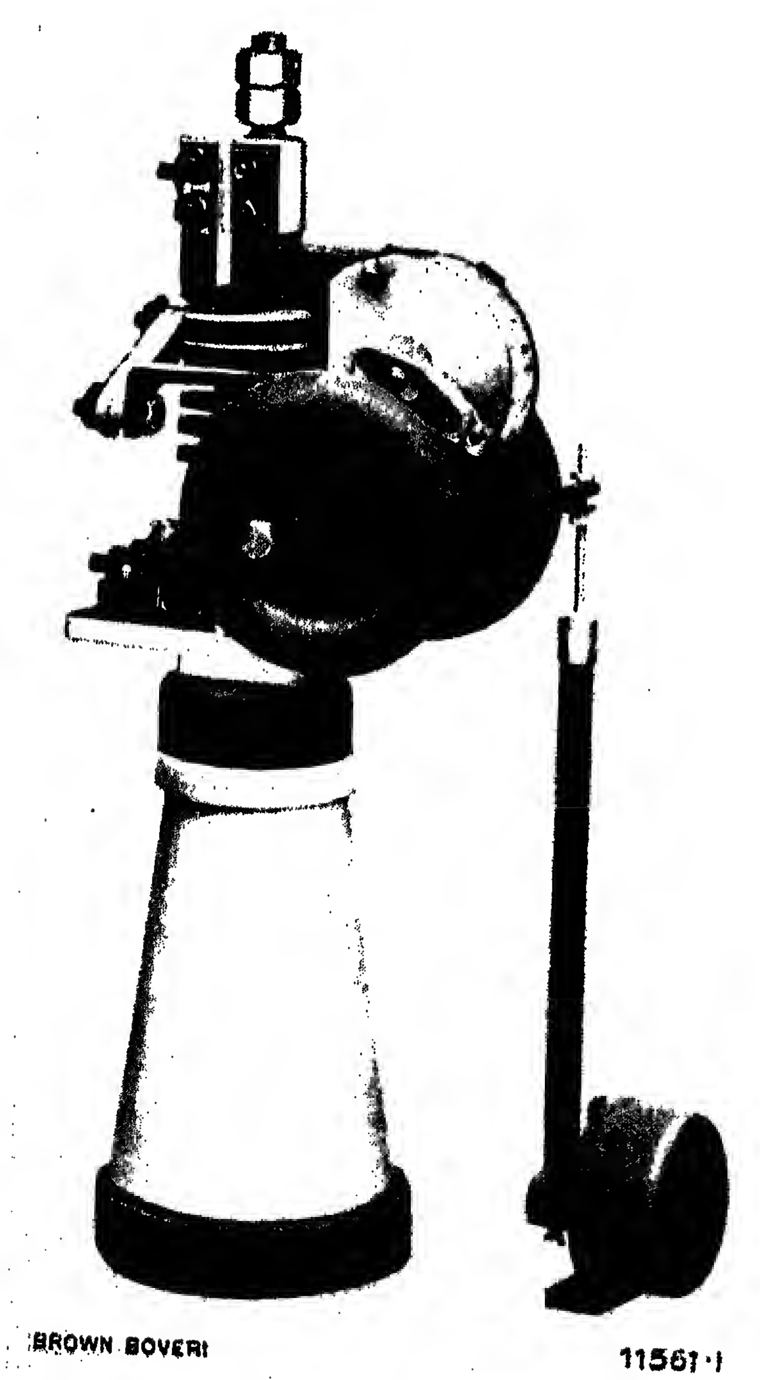


Fig. 12. — Series relay Type H 4 arranged to operate a contact device.

For currents exceeding 1000 A, the dimensions of the magnet coil would become excessive. In such cases, a 5-A coil is used, connected to a current transformer placed above the switch insulators.

Under certain conditions, it may be advisable for the tripping of one or several of the oil switches to depend upon some current other than that flowing through the switch itself. In such cases, the relay is arranged as shown in Fig. 12. It actuates a contact which closes the circuit of the trip coil of the switch to be operated.

Series relays are used principally in substations, but they are also used in small power stations without auxiliary sources of current.

IV. OVER-CURRENT DEFINITE TIME-LIMIT RELAY, TYPE H 2.

Fig. 13. — Over-current relay Type H 2.

Relay Type H 2 (Figs. 13 and 14) was put on the market at a somewhat later date than the series relay, to which it is similar in design and operation. It differs, however, from relay Type H 4 by being designed for connection to a current transformer. Instead of actuating the tripping mechanism mechanically, the lever b_1 operates, through the rod f, a

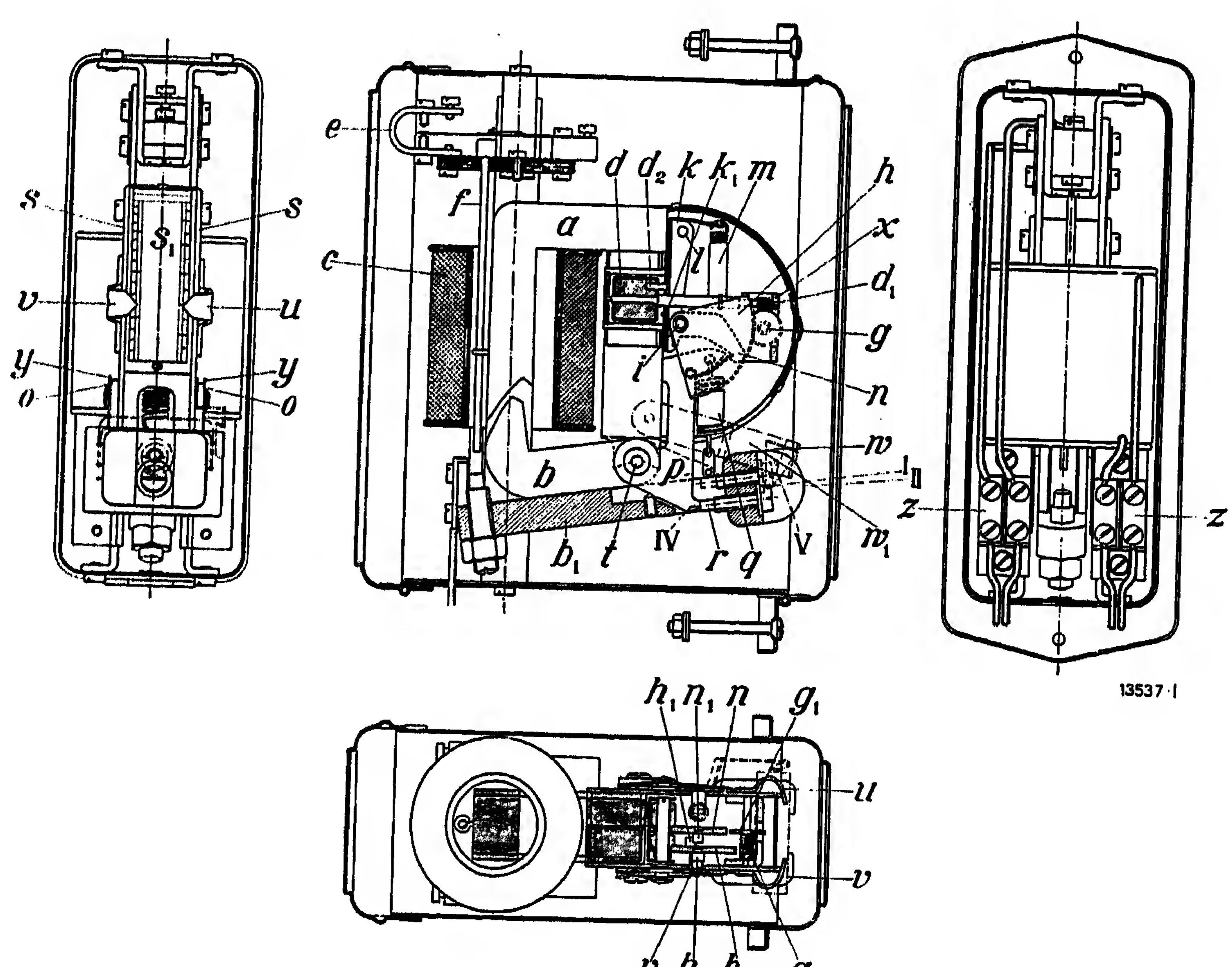


Fig. 14. — Over-current relay Type H 2.

contact e, which either closes or opens an auxiliary circuit according to the method of tripping employed. The narrow shape of the relay casing, similar to that of an edgewise switchboard instrument, makes it very suitable for mounting in switch panels or switch desks. The glass cover over the front is hinged to permit of adjusting the two pointers u and v, by which the pick-up current and the time limit are set, and also the disc w, for indicating which of several relays has operated. A similar cover of metal protects the relay terminals, which are situated at the back of the casing.

The strength of the pick-up current can be set between 1·3 times and twice the rated current. As with series relays, the time limit is practically independent of the strength of the overload. If the latter ceases before the time lag has elapsed, the armature of the magnet immediately returns to the rest position. If the screw r be placed in the threaded hole V, the relay makes contact instantaneously when the overload exceeds three times the rated current.

V. REVERSE-POWER RELAY, TYPE B 2.

Like the over-current relay Type A 2 the reverse-power relay B 2 is not a new type of apparatus, but is built to a design which has given ample proof of its reliability in practice. Formerly, this type of relay was not much used, its duty then being either to actuate a warning signal when a switch opened, or, by tripping a switch, to prevent a reverse flow of energy at certain points in a system.

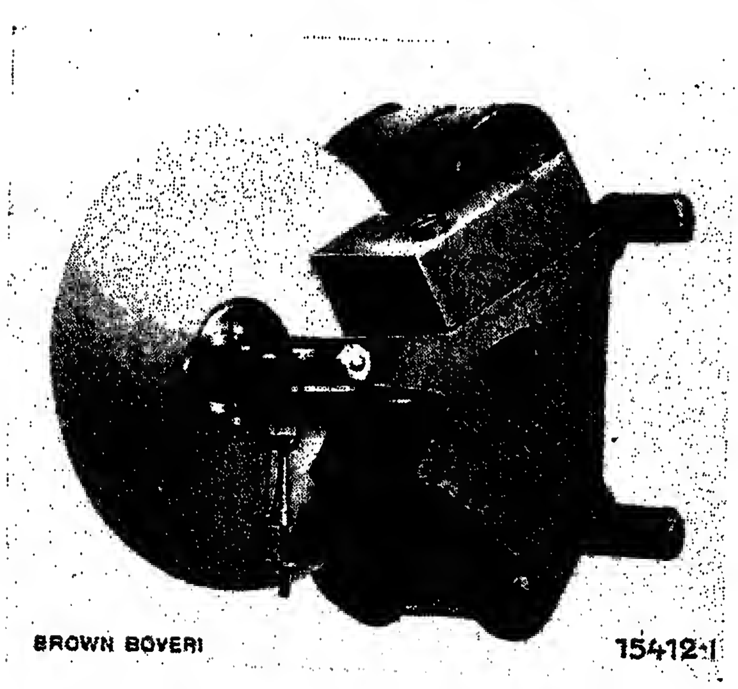


Fig. 15. — Reverse-power relay Type B 2.

An improved design of this relay has been used with good results for cutting out and demagnetising defective generators and the transformers directly connected to them. Thus it was obviously a suitable apparatus for similar duty in the selective cutting out of defective line sections. By still further improvement, the relay has now been made so sensitive that it operates during overloads even when the pressure drops considerably, as happens with short circuits, for example. As in the over-current time-limit relay A 2, the mechanism of this relay consists primarily of an aluminium disc rotating between the poles of two

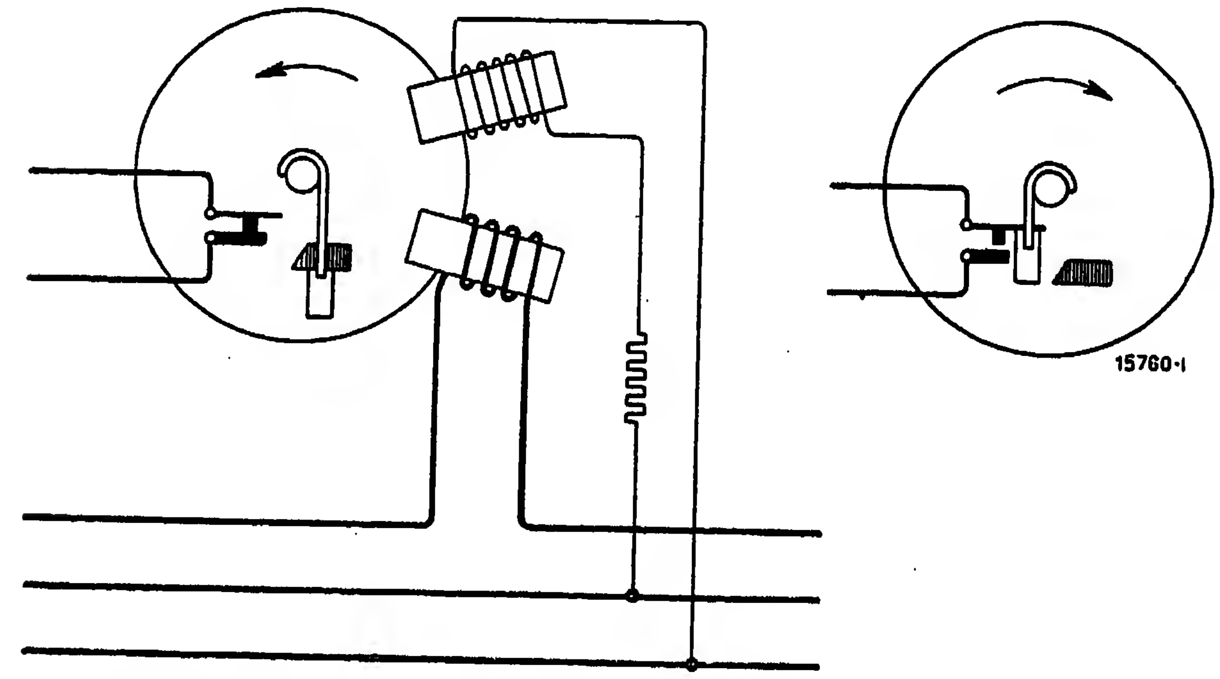


Fig. 16. — Reverse-power relay on a three-phase system.

laminated electro-magnets (Figs. 15 and 16). The winding of the lower magnet is energised from a current transformer and the winding of the upper magnet from a pressure transformer. With the help of a series ohmic resistance, connections are so made that the angle between the current vectors of the two coils is sufficient to produce rotation of the disc however poor the power factor of the line in question may be. When energy flows through the line in the "forward" direction, the disc rotates so that the thread is wound up on the disc spindle from the back, the

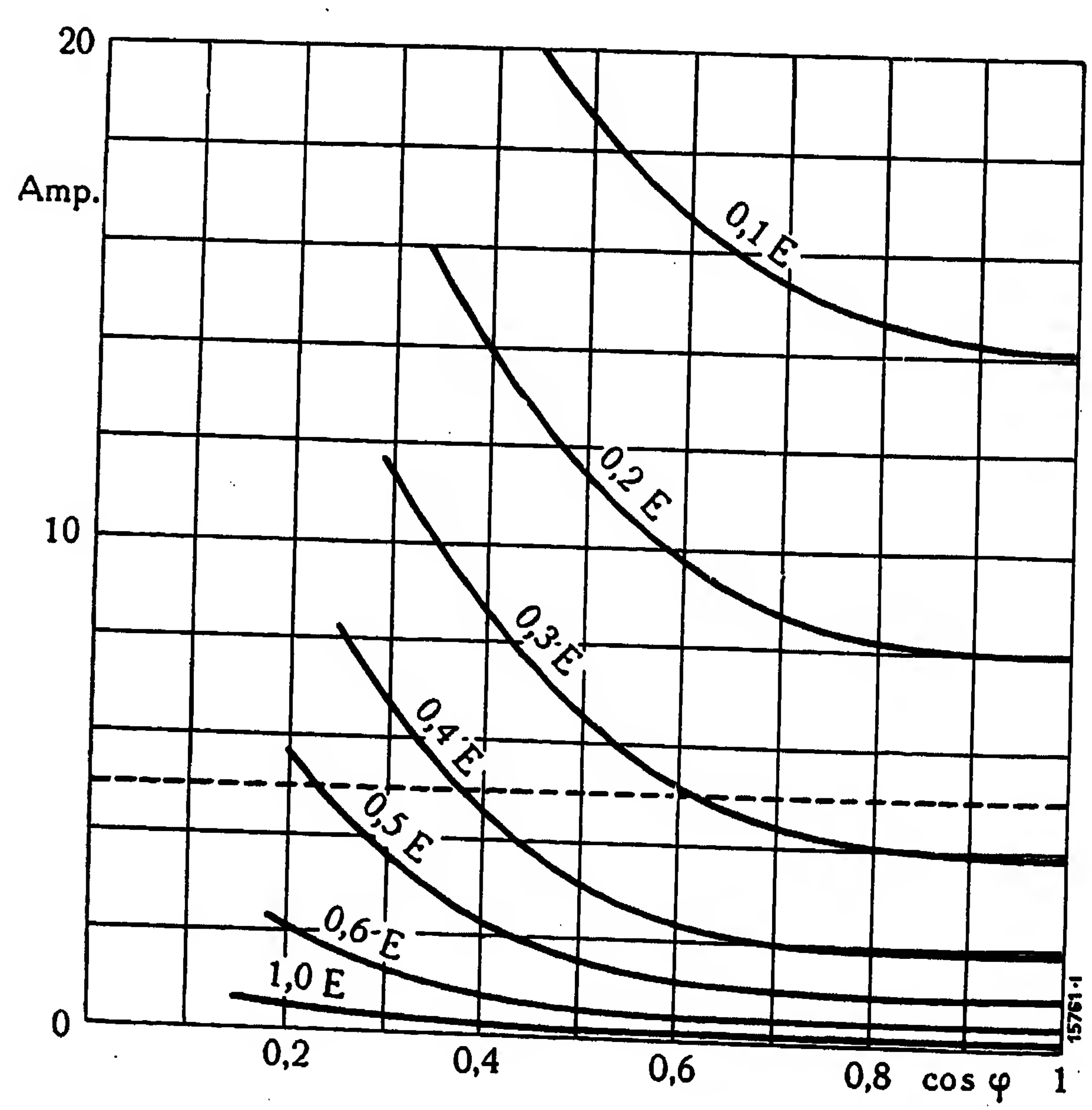


Fig. 17. — Pick-up currents of the reverse-power relay, frequency 50 cycles per second.

counter weight coming up against a fixed stop, which arrests the further movement of the disc. When energy flows in the reverse direction, the disc rotates in the opposite sense and carries the counter weight up, past the fixed stop, until it reaches a contact which it either closes or opens, according to the system employed.

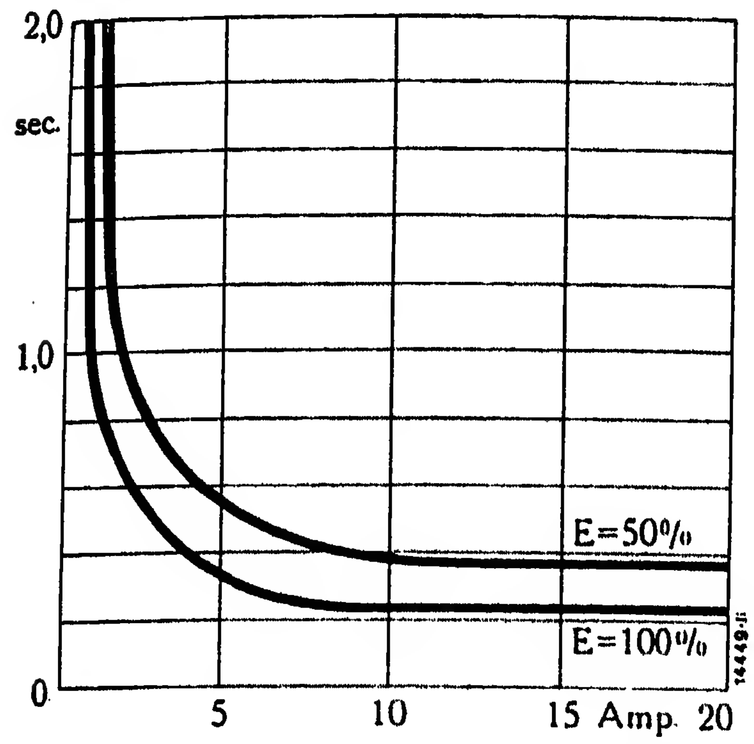


Fig. 18. — Time lag as a function of the current for a reverse-power relay, frequency 50 cycles per second.

No device for setting the pick-up current is required with the reverse-power relay. In Fig. 17, the pick-up current of the relay in a three-phase line with balanced load is plotted as function of the power factor for various values of the pressure. If required, the current necessary to actuate the apparatus can easily be increased by adding to the counter-weight, and the time lag can be altered by clamping the counter-weight higher or lower on the thread. The time lag naturally depends upon both the strength of the current and the pressure, as shown Fig. 18, from which it is seen that the time taken for the disc to complete its rotary movement does not exceed 0·5—1 second under short-circuit conditions when the travel of the counter-weight is made sufficiently short.

VI. METHODS OF TRIPPING.

On three-phase lines, when the neutral point is not earthed, over-current protective devices are only required on two phases. These are sufficient for coping with either the so-called three-phase short circuits, or with short circuits between two conductors (two-phase short circuits). If a neutral point of the system is earthed, all three phases must be protected.

The contact apparatus is arranged either for "closing contacts", which are normally open and are closed upon the operation of the relay, or for "opening contacts", in which the opposite is the case. In the following paragraphs the systems of connections most commonly used are explained with the help of four diagrams showing two-pole protection of three-phase systems. The simple tripping solenoid has proved so efficient in practice that all complicated devices, such as double or triple tripping solenoids, which enjoyed a certain popularity at one period,

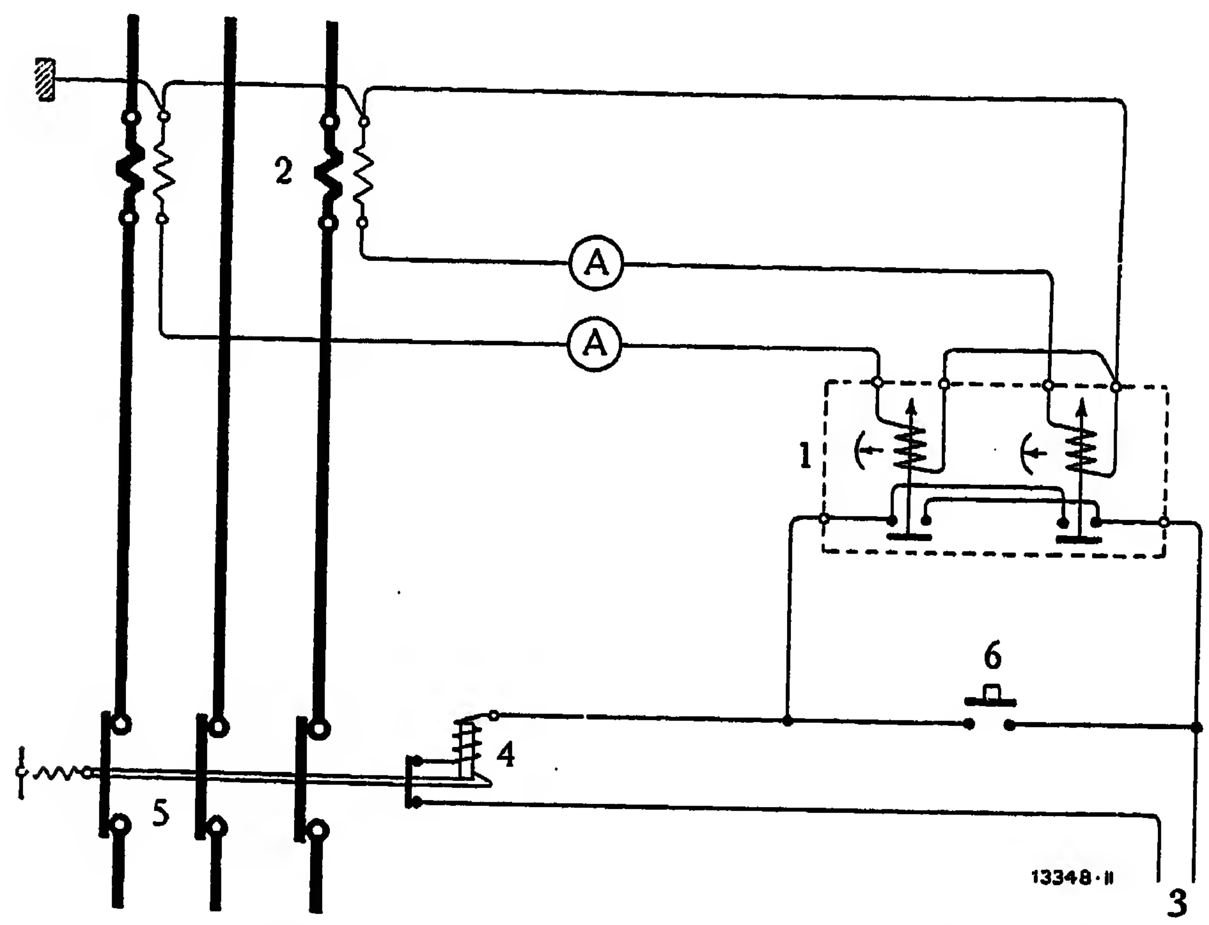


Fig. 19. — Over-current relay for tripping by auxiliary current.

1. Over-current relay with closing contact.
2. Current transformer.
3. Auxiliary source of current.
4. Tripping solenoid with contact.
5. Oil switch.
6. Push-button switch with closing contact.

are quite unnecessary. It is easy by analogy to derive suitable systems of connections for single-phase or two-phase plants, for three-pole protection, or for the combination of several types of relays.

1. Auxiliary-current tripping (Fig. 19) is the simplest of all tripping methods and should be applied to all plants of any importance. A source of direct or alternating current, completely independent of the plant to be protected, must be available. Either a storage battery, or an alternator or direct-current dynamo driven by an independent engine forms a very suitable source of auxiliary current, but a generator driven by a motor connected to the system to be protected is obviously unsuitable. Should no other source of current be available, a small battery for switch tripping only can be specially installed.

With auxiliary-current tripping, the current circuit of the tripping coil is closed by the relay contact. After tripping has been effected, the circuit in question should not be broken again by the relay contacts but by special auxiliary contacts placed on the shaft of the oil switches, such as are used on the handwheel control of Brown Boveri oil switches with tripping solenoids, or on motor or solenoid remote controls for oil switches.

2. Relay-current-transformer tripping (Fig. 20) is used in plants possessing no auxiliary source of current, where under-voltage tripping is undesirable, and where, for special reasons, series relays should not

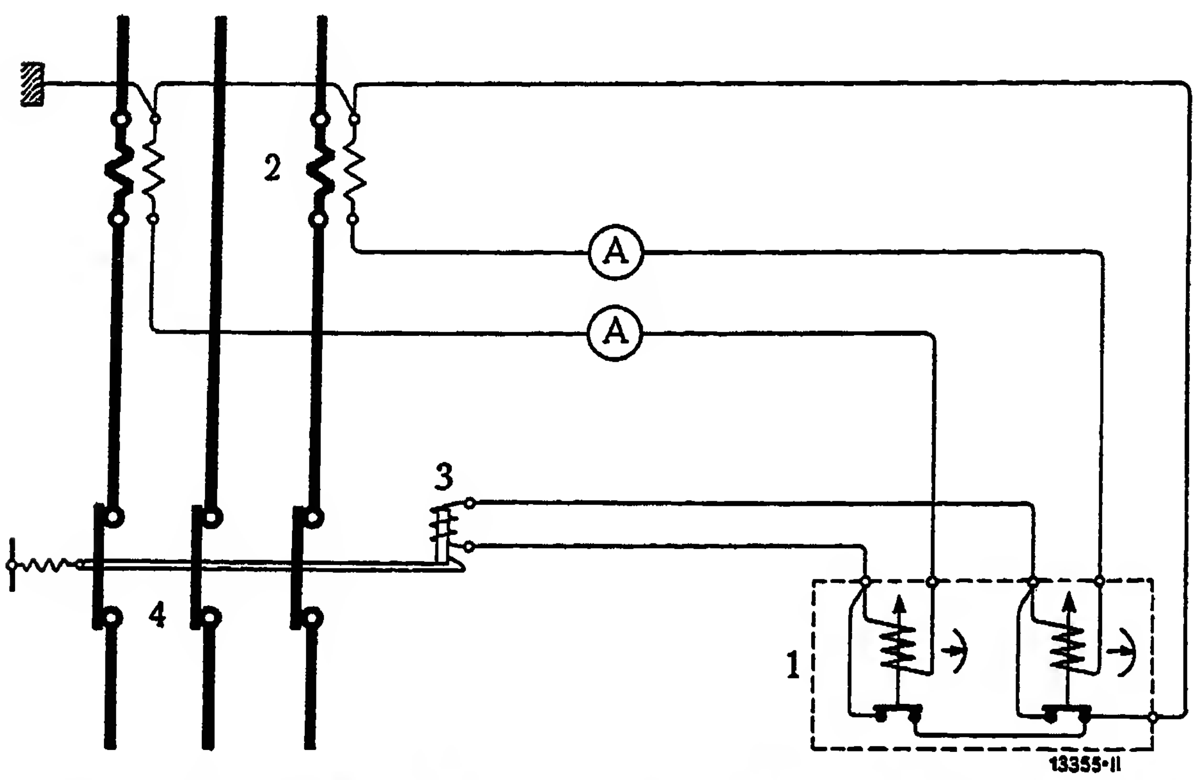


Fig. 20. — Over-current relay for tripping by relay current transformer.
1. Over-current relay with opening contact.
2. Current transformer with secondary current of 1 A.
3. Tripping solenoid.
4. Oil switch.

be used. Normally, the contacts of the relay are closed and, in this position, they shunt the coil of the tripping solenoid. Upon the relay functioning, the contacts open and the secondary current of the current transformer energises the tripping coil, which immediately releases the oil switch. To prevent the relay contacts from welding together, on account of the short-circuit current which flows through them immediately before they open, a current transformer stepping down to 1 ampere must be used in the place of the usual 5-ampere type. It is desirable, however, only to employ this method of tripping in

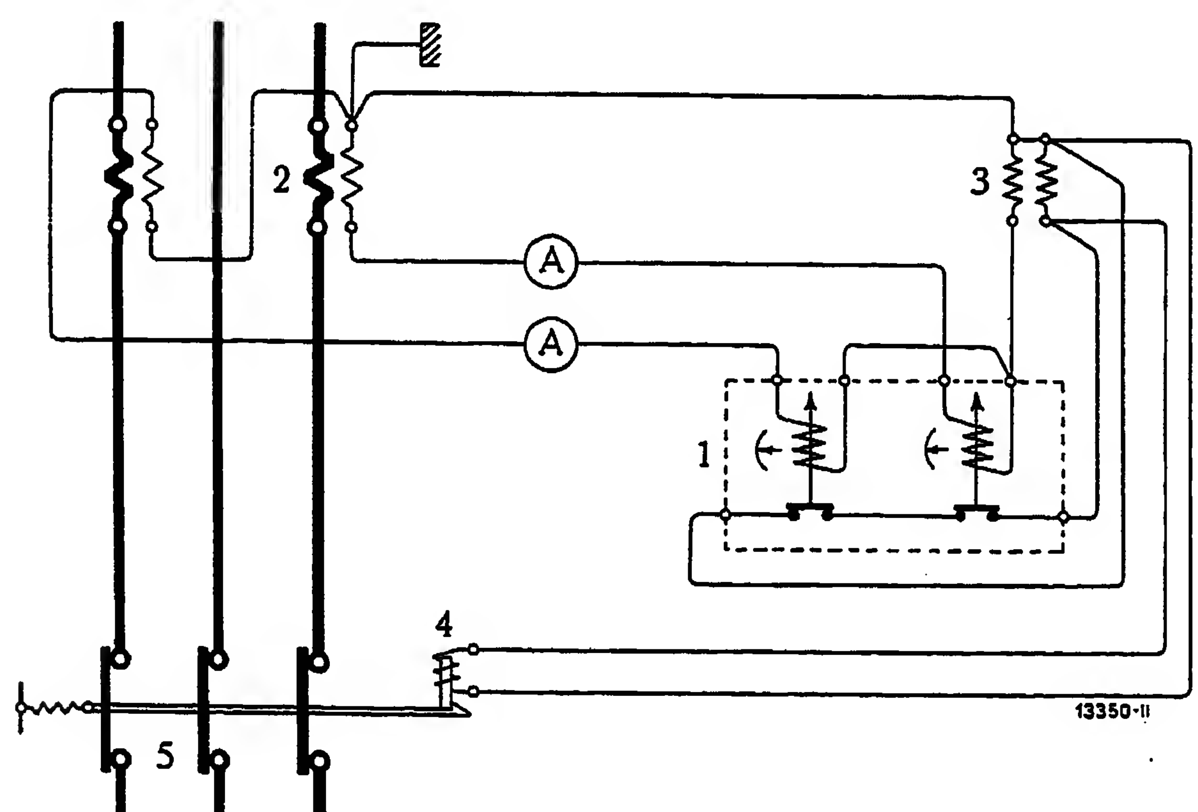


Fig. 21. — Over-current relay for tripping by auxiliary current transformer.
1. Over-current relay with opening contact.
2. Current transformer.
3. Auxiliary current transformer.
4. Tripping solenoid.
5. Oil switch.

cases where no short circuits exceeding 6 times the rated current are expected, as, otherwise, excessive pressures and arcing can occur upon the breaking of the contacts.

3. Auxiliary-current-transformer tripping (Fig. 21) is not subject to the above restriction. The secondary current is transmitted to the tripping coil through an auxiliary current transformer with a ratio of 5/1 amps., which is so designed that, even under the heaviest short circuits, the current in the secondary circuit does not exceed an admissible figure. Thus, the contacts shunting the tripping coil are protected against welding together and against excessive arcing. Neither this method nor the previous one is suitable for three-pole protection.

4. Under-pressure tripping can be employed alone or in conjunction with over-current relays, as shown in Fig. 22, but only for the protection of plant where even a passing pressure drop necessitates switching out and restarting. If an independent source of auxiliary current is not available in transformer

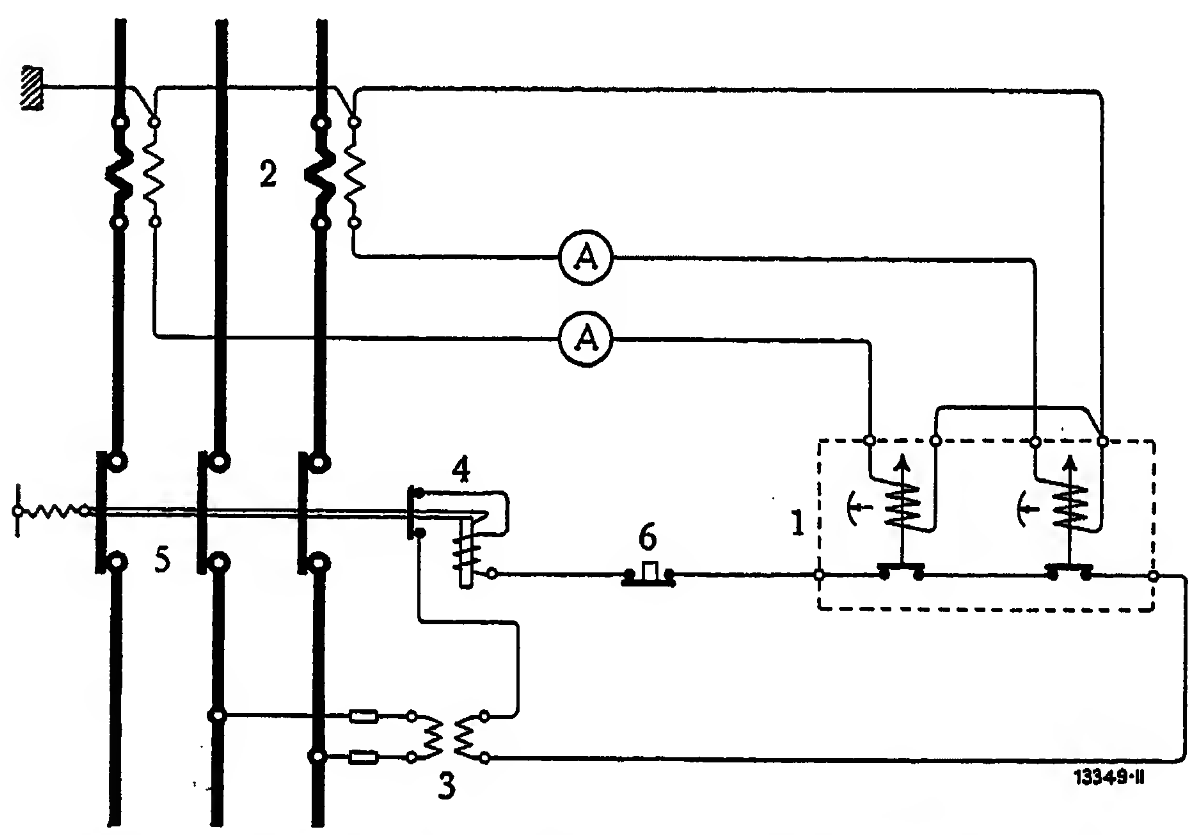


Fig. 22. — Over-current relay with under-pressure tripping.
1. Over-current relay with opening contact.
2. Current transformer.
3. Pressure transformer.
4. Tripping solenoid with contact.
5. Oil switch.
6. Push-button switch with opening contact.

stations, it is better to put in series relays, as the use of under-pressure tripping would cause the unnecessary opening of many switches as the result of the pressure drop accompanying every short circuit. With under-pressure tripping, the tripping solenoid of the oil switch is continually excited by a pressure coil. If the pressure drops considerably, the armature of the solenoid falls, releasing the catch

and tripping the switch. When used in conjunction with an over-current relay, the armature is caused to drop by the opening of the contacts of the over-current relay, these forming part of the tripping circuit. The switch can also be tripped from any point desired by means of a push-button.

With machines such as synchronous motors, rotary converters, etc., which remain excited during the shutting down operation, the frequency falls with the speed. Despite the falling pressure, the magnetisation of the tripping solenoid on the oil switch remains the same, so that the switch would only be tripped when the machine had almost stopped. To make the tripping independent of the change in frequency, a non-inductive resistance is placed in series with the tripping coil. When switching in again, the armature of the solenoid must be lifted mechanically.

VII. SELECTIVE PROTECTION.

There are various methods of making the over-current protective equipment act selectively, that is to say, so that only those switches which isolate the defective section of line trip automatically when a short circuit occurs. Some of these methods have been known and applied for a long time and are as old as the automatic circuit breaker itself. On the other hand, the terms *selective protection* and *selective relay* have only come into common use recently.

1. Selection by graduation of the pick-up current.

When tripping coils are used which carry the main current and operate instantaneously upon a given current being exceeded, selective operation is obtained by graduating the tripping currents of the various coils. This is possible for distribution systems

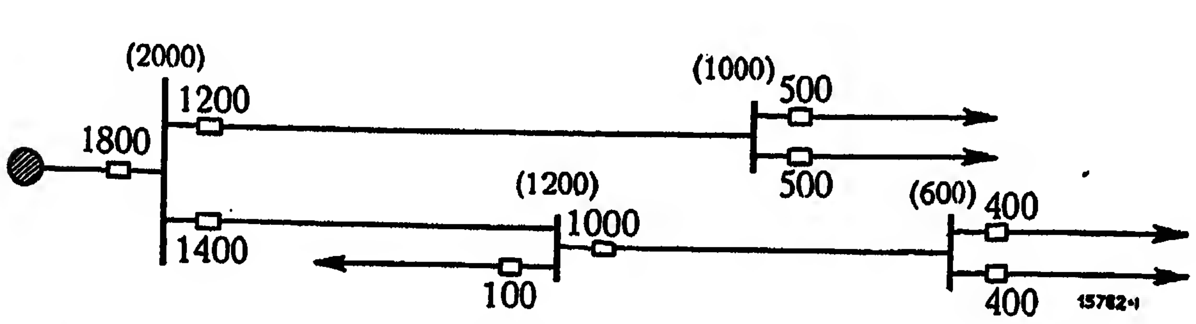


Fig. 23. — Distribution system fed from one point and equipped with instantaneous relays.

either consisting of subdivided lines fed from one point only, such as shown in Fig. 23. In such cases, the switches nearest the generating station are provided with tripping coils which act only under heavier currents than those of the other switches. The pick-up currents of the other switches are so graded that they are smaller the further the distance of the switch from the generator. (Each little rectangle in Fig. 23 represents a switch with an instantaneous over-current relay and the numbers not in brackets are the currents under which they operate.) This kind of protection has been in use for a considerable time. The common error committed, however, is to set the strength of the tripping current according to the admissible overload. The obvious result is that, when a short circuit occurs at the end of the line, with a resulting current much bigger than that admissible under overload conditions, all the switches trip at the same time. Owing to the difficulty or even impossibility of estimating what the short-circuit current at different points on the system will be (figures in brackets), or because of inadequate means of adjustment on the relays for heavy currents, recourse is often had to the very dubious practice of simply blocking the tripping gear of certain switches so as to avoid general interruptions of service.

Nevertheless, the method of graduating the tripping current is of value when combined with other devices. When used alone, it is only advantageous in plants always fed by the same generators or set of generators, in other words, in systems where the short-circuit current can be estimated and will remain the same. Protection against overloading must then be provided by suitable apparatus placed in the secondary distribution system or at the points of consumption. If, now, the tripping currents have been chosen to correspond to the short-circuit currents which would flow at different points on the system (figures in brackets), the switches nearest the generating station will obviously not be tripped when a short circuit occurs at a spot remote from the station. In alternating-current plants where secondary relays with a limited range of adjustment are used, — whether instantaneous relays or thermal time-limit relays, which also act instantaneously with currents several times normal,—graduation is obtained by a suitable choice of the ratio of the various current transformers. It is clear that, with selective protection of this kind, the load which each switch can safely break must be in suitable relation to the momentary short-circuit current to which it will be subjected.

2. Selection by graduation of the time limit.

There is another method which can be used to make the automatic tripping of the switches selective. This method requires relays which trip the switches after a given time (time-limit relays) instead of acting immediately when a short circuit or overload occurs.

If, for example, on a subdivided line fed from one point, the time lag is greatest for the switch nearest the power station and progressively shorter the further away the switches are from the station (each circle in Fig. 24 is a switch with over-current relay and the corresponding figures are the time lags in seconds), the short circuit only causes that switch to open which isolates the defective section from the power station, as the more remote relays have no reason for functioning, the current at these points not being excessive. It is true that the relays between the defective section and the power station will also act, but, owing to the longer time limit for which they are set, they will not trip their respective switches. This selective method only acts with any degree of precision if the time limits be adjusted for at least 0·5—0·6 seconds difference from switch to switch. Of this, 0·2—0·3 seconds are required to trip the switch, and the remainder is an allowance for inaccuracy in the time lag.

If the time lags are graduated closer, there is a danger that the switch set for the next longer time lag will act before the actual switch involved. To prevent the system from being too long subjected to the short-circuit current, and the induction and synchronous motors connected to it from falling out of step, the time lag set must be as short as possible. In Fig. 24 and the following wiring diagrams, the time lag is taken as being 0·5 seconds. This assumes that the switches are so dimensioned that they can break the short-circuit current which, after so short a time, has not yet come down to its steady value. If this should not be the case, the time lag must be increased to a full second at the least.

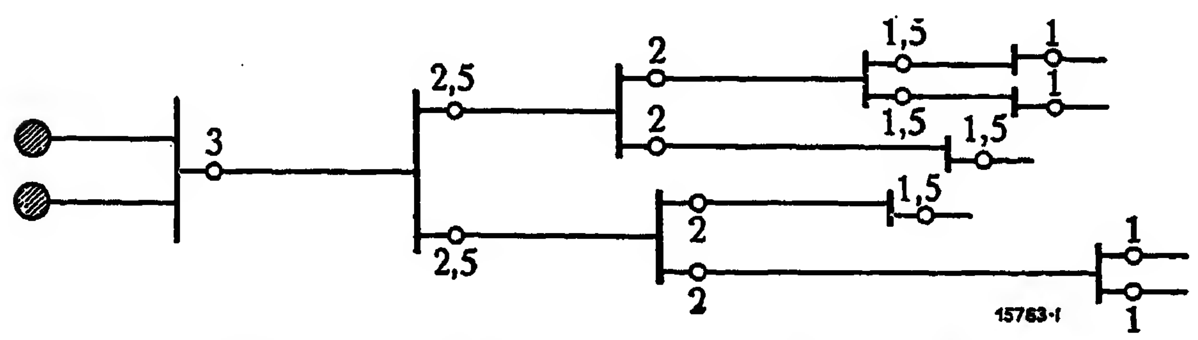


Fig. 24. — Distribution system fed from one point and equipped with time-limit relays.

If the longest time lag (that of the relay on the switch at the point where the various lines branch out from the station) be assumed to be three seconds, which appears reasonable for overhead lines when the total output of the generators in the central station is not unusually large, and if, as shown in Fig. 24, only the outgoing lines are provided with automatic switches, this selective method has a scope of up to five or six sections of line in series. Should the generators be provided with current-limiting regulators, a short circuit only results in a relatively small steady current and the time lag of the oil switches can be set for 4—5 seconds without danger of damage. Thus, the scope of the system can be increased up to seven or eight line sections in series, or the difference of time lags between the switches, and consequently the reliability of the selective action can be increased.

Cable lines are subject to heavier short-circuit currents than overhead lines owing to the lack of inductive resistance. They also present inferior cooling facilities, and for these reasons they heat up much quicker under short circuit. Thus, the longest permissible time lag on cable systems is not more than 2 seconds, which limit can be increased to about 3 seconds if the power station be equipped with current-limiting regulators. With cable systems, the range of protection is therefore reduced to 3—4 or 5—6 line sections in series.

The pick-up current of relays on high-tension overhead lines is set, for practical purposes, at 160—180 % of the normal current strength, and at 140—160 % if current-limiting regulators are used in the power station. If, however, the output of a given line be more than 2—3 times that of a generator in the power station, it is advisable, if only one or two generators are working, to make sure that the continuous short-circuit current which may occur, exceeds the tripping current for which the relay is set. If this is not the case, the relays will not function at all. In calculations of this kind, the continuous short-circuit current flowing, when a short circuit takes place near the station, can be taken as being from 2 to 2·5 times the rated current, with generators driven by water turbines, and 1·6 times to twice the rated current with steam turbo-generators. When the short circuit occurs at a point remote from the station, the short-circuit current diminishes

with the pressure drop on the line. In plants equipped with current-limiting regulators, the continuous short-circuit current which the generators have to withstand is given by the setting of the regulators, however far from the station the point of short circuit may be. It is advisable to set the pick-up current somewhat lower in cable systems.

When setting relays, attention must be given to the fact that if a short circuit occurs on a line fed from the same bars as an unaffected line to which motors alone are connected, the latter may be subject to a current which exceeds the tripping current, as a result of the big pressure drop, and this may cause an undesirable tripping of switches on the unaffected line. Somewhat longer time lags should be allowed on such lines, if possible, as well as heavier pick-up currents. If this is not feasible, the relays of the biggest motors may, in extreme cases, be set for a smaller current or shorter time lag so that they trip the motor switch sooner and so prevent the main switch from tripping. The apparatus most suitable for separate lines and ramified systems as in Fig. 24 is, without question, the series definite time-limit relay, Type H 4, builton to the switch. With this system, without either current transformers, auxiliary sources of current, or tripping magnets, the much desired simplicity and easy supervision of branching stations is attained. The use of secondary over-current relays like Type H 2 or A 2 should only be considered for big substations where it may appear desirable to unite instruments and relays on a switchboard and when a storage battery is available to feed the tripping circuits.

For the selective protection of subdivided lines and ramified systems composed of single (not parallel) lines, over-current relays with time-limit settings graded downwards from the power station are sufficient when the number of line sections in series is not too great.

For constructive and economic reasons, the sections of the overhead line and cable conductors should not be increased beyond certain limits. From the point of view of reliability of service, the energy of the power station is often carried to the principal distributing points by *two or more parallel lines* placed beside each other or at a certain distance from one another. The selective protection equipment has, therefore, to meet somewhat different conditions than those hitherto described, because a short circuit will now not be fed direct from the power-station end only, but also from the other extremity of the line section, through the other lines in parallel with it. In order to isolate the defective line section from the other extremity as well, automatic oil switches placed in

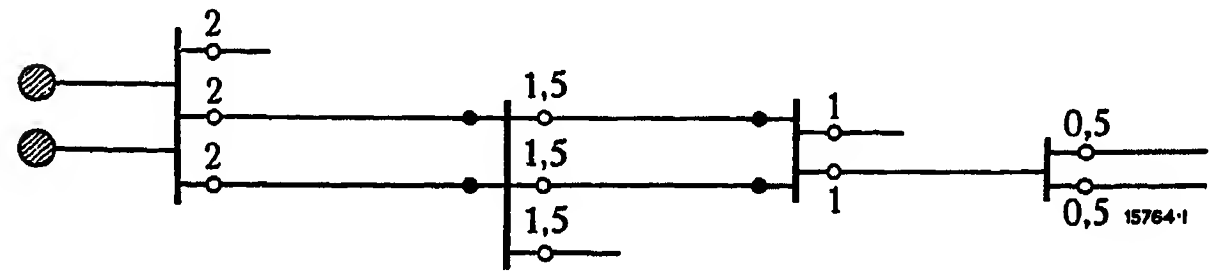


Fig. 25. — Double line system fed from one point.

the line sections at the points where they begin, as in Fig. 24, are no longer sufficient. They must be supplemented by automatic switches placed at the other end. For this purpose, reverse-power relays are used, as shown in Fig. 25 (black circles). These relays must have as small a time lag as possible (see page 9). The detailed diagram of connections at a point where there are one outgoing and two incoming lines

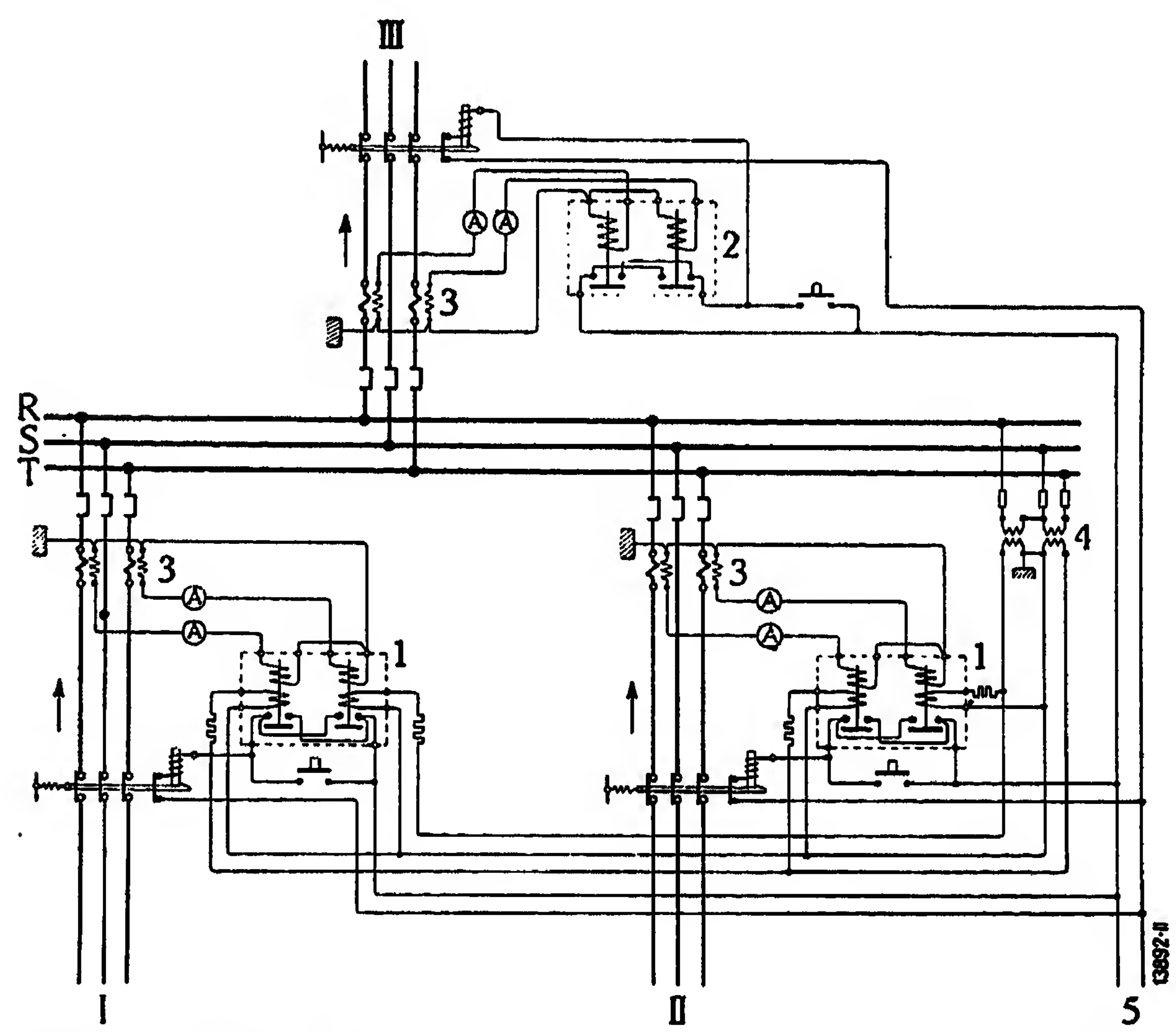


Fig. 26. — Selective protection of a branching station with unidirectional energy flow.

is shown in Fig. 26. The reverse-power relays are designed to trip with certainty, even when the pressure drops to only a fraction of its normal value, as happens during a short circuit.

By far the most common short circuits are those between two lines. In order that the voltage across the pressure coil of the reverse-power relay may be as high as possible under these conditions, the pressure

coil is connected to conductors R and S, for example, while the current coil of the same relay is placed in the opposite phase T. When a short circuit occurs between S and T or R and T the pressure between

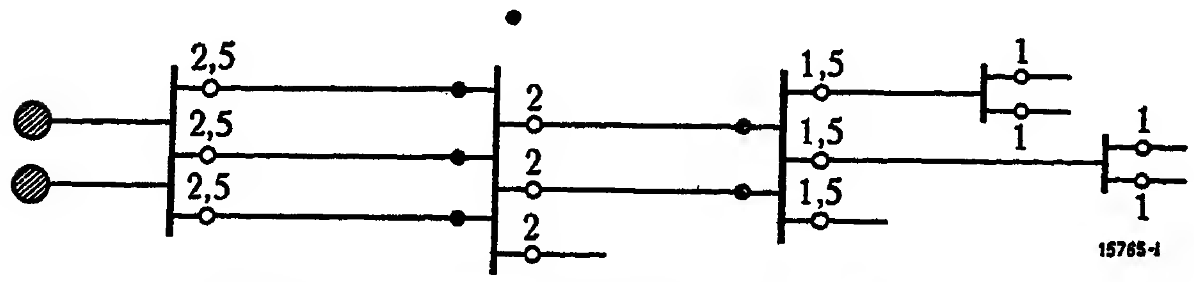


Fig. 27. — System composed of parallel lines fed from one point.

R and S retains a certain value. This kind of protection can also be used to advantage for three or more parallel lines, as is shown in Fig. 27.

For the selective protection of two or more lines in parallel in ramified systems, ordinary over-current relays can be used at the beginning of the line sections and reverse-power relays at the end, the setting of the former being graded downwards from the power station.

The *parallel operation of power stations* and distribution systems is of such great economic importance to-day that disturbances must be prevented from spreading, if possible, and measures sought to shorten their duration. The isolation of a defective section can be carried out by simple means if the two power stations are linked up by a line used for energy compensation only, that is to say, to which no distributing lines are connected. Over-current relays suffice in this case, as shown in Fig, 28. Care must be taken that the time lags of the switch relays on the compensating line are one step higher than those

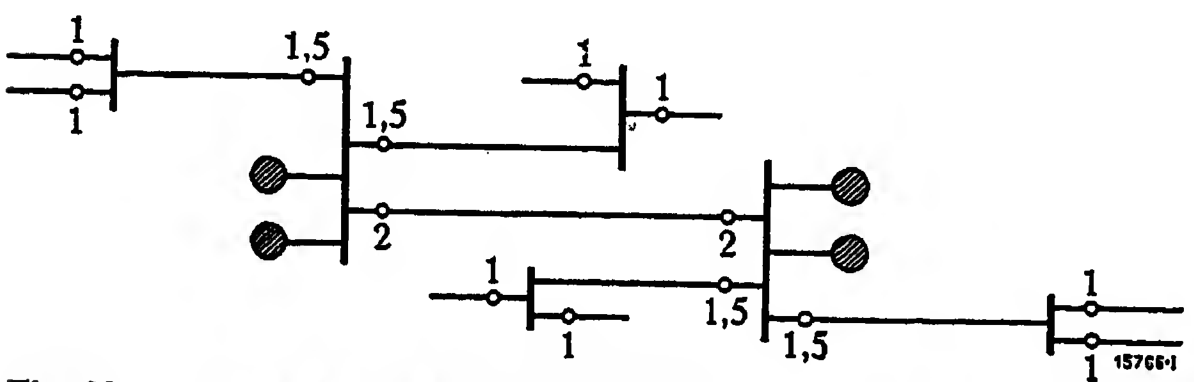


Fig. 28. — Power stations directly linked up by a compensating line.

of any of the other switches on the system, in order to make sure that the two stations will remain linked up when a short circuit takes place on either of the two distributing systems.

If the position of a power consumer should make it necessary to connect a branch line to the compensating line, the switch on this branch alone is made to trip automatically, but not the neighbouring ones. If a short circuit occurs on the compensating line, the consumer is therefore left without current.

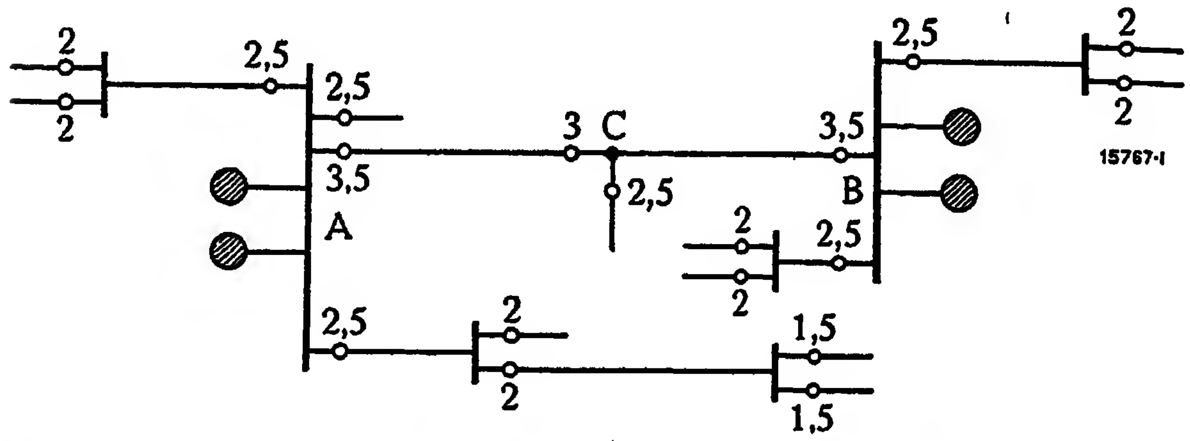


Fig. 29. — Power stations linked up by a compensating line on which a branch line is connected.

If the consumer branched at C (Fig. 29) is of sufficient importance, one of the neighbouring switches is made to trip automatically as well, so that, if a short circuit occurs in section A—C, the consumer in question is supplied from one station through B C and is only cut off if that section also be affected.

In this case, the time setting of the relays on the power-station switches must be somewhat longer than that of any other switch on the compensating line. It is obvious that it would be useless to place automatic tripping devices on both switches adjacent to the branch line, as it would be impossible to find a time setting graded to meet every eventuality.

The selective protection of a system in which two power stations are connected by a single line, used only for compensation, can be carried out by simply grading the time lags of the different relays.

3. *Improvement of selective action by inverse time-limit relays.*

The desire to make selection more reliable in operation with finely graded time lags and also to extend the system to a bigger number of line sections in series by finer graduation gave rise to the idea of utilising the relation between the time limit of a relay and the strength of the short-circuit current in

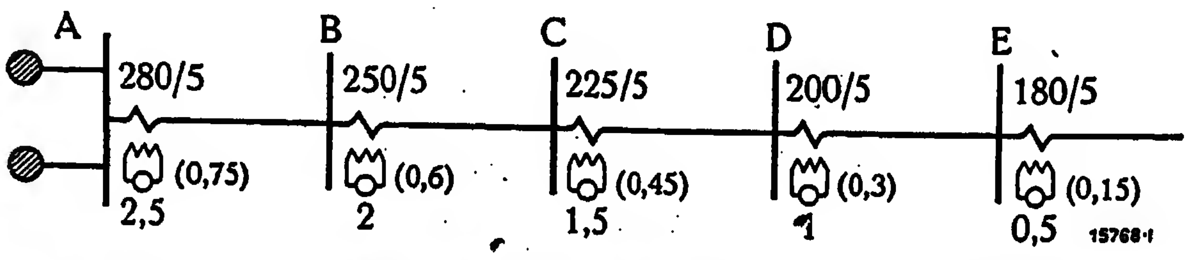


Fig. 30. — Line sections with graduated current transformers.

such a way as to increase practically automatically the difference of the time lag between the switch closest to the disturbance and the next. With this object, the primary current of the current transformers is decreased as indicated in Fig. 30, the further they are from the power station, so that a short circuit at the end of a line results in a bigger secondary current in the corresponding relay than a short circuit at the beginning of the line. When the over-current time-limit relays, Type A 2, as described

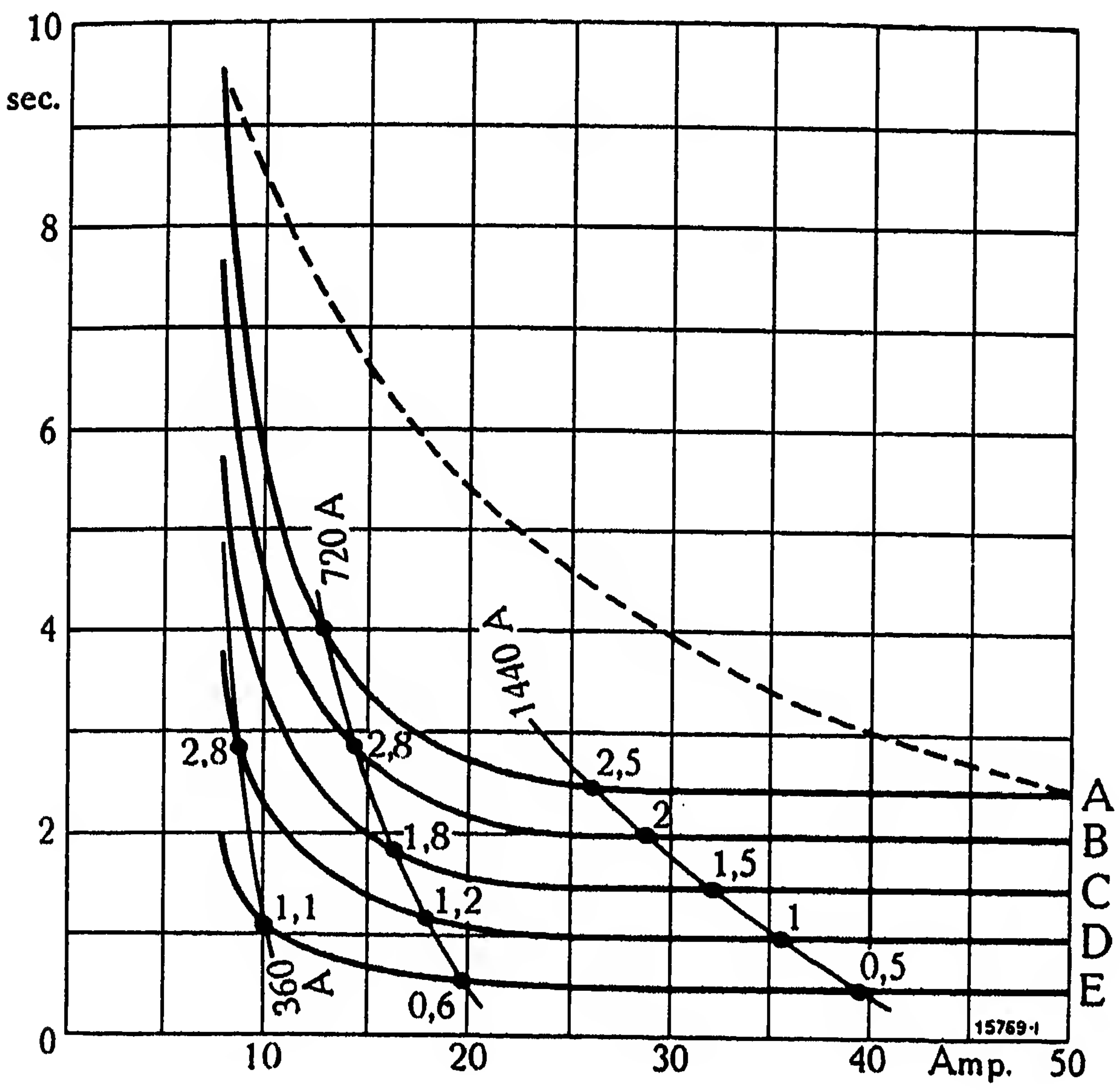


Fig. 31. — **Changes in the time lag of an inverse time-limit relay for different short-circuit currents.**

on pages 3 and 4, are used, all the pivoted poles of these relays are turned, for example, to the figure 100 (which corresponds to a pick-up current of 8 A = 1·6 times the rated current) and the travel of the counter weight (figures in brackets) is set so that when a short circuit of 5 times the rated current or more occurs (secondary side 25 A or more) there is a difference in time lag of 0·5 seconds. As a result of this, the relays of the various switches act according to the current-time curves shown in Fig. 31. If now, a short circuit occurs at the end of the line, equal to twice, four, or eight times the rated current of the current transformer placed at that point, which is dimensioned for 180/5 A, this means currents of 360, 720 or 1440 A, which produce, at the point E, secondary currents of $\frac{360}{180} \times 5$ etc. = 10, 20, or 40 A respectively. At D, where the ratio of the current transformer is different, these short circuits produce secondary currents of $\frac{360}{200} \times 5$ etc. = 9, 18, or 36 A respectively. Similarly, at C, the secondary currents will be 8, 16 and 32 A. If the times corresponding to these currents are determined on the curves in Fig. 31, and if lines are drawn joining up the time limits corresponding to each short-circuit current on the different relays, the steep curves marked 1440, 720 and 360 are obtained.

These curves show that the original time-limit difference between E and D, which was 0·5 seconds for a short circuit 8 times the rated current at the end of the line remains as before; for a short-circuit current 4 times normal, however, it increases from 0·5 to 0·6 seconds, and increases further from 1·2 to 1·7 seconds for a short circuit of twice the rated current. The automatic increase in the difference between the time lag is thus only apparent when the short-circuit currents are low and not at all for heavy short-circuit currents.

With a straighter current-time curve such as that shown in dotted line in Fig. 31, an improvement could also be effected for heavier short-circuit currents. It does not seem advisable, however, to sacrifice the simple construction of the relay for this purpose, the more so as the effect desired cannot be obtained for every short-circuit current however strong.

The property possessed by this relay of a time lag which varies inversely as the short-circuit current is of far greater importance, when considered in relation to current surges of short duration, such as occur during switching operations or slight disturbances. Definite over-current relays set for a short time limit would inevitably act and trip the switches, under these conditions. Inverse relays do not do so for such short disturbances because the time lag under such conditions is long compared with the duration of the disturbance.

The advantage of the inverse time-limit relay from the point of view of greater reliability in selection, for lines supplied from one end only

and for ramified distribution systems, is limited to short-circuit currents of less than 4 times the rated current. On the other hand, they present a somewhat higher degree of reliability in avoiding undesirable interruptions of service when current surges of short duration occur.

The advantages of inverse operation are much greater when short circuits occur on the branch lines of systems fed from two or more points. This is owing to the fact that the current transformers inserted on the branch lines, and constructed for much smaller primary currents than those of the main lines, carry the total short-circuit current, and the relays which they feed trip much quicker, while each of the separate lines from the power station to the branching points carries only a part of the short-circuit current. This is often so throttled by the big pressure drop in the branch that the relays in these main lines only act slowly or not at all. In many distribution systems which have been successively extended after considerable intervals of time, or in cases where stations and systems, formerly independent, have been linked up, certain parts of the network may be equipped with definite time-limit relays and others with inverse time-limit relays. This circumstance can result in the tripping of a switch near the power station by one of the definite time-limit relays on relatively light short circuit, while, owing to its inverse action causing its time lag to be longer, an inverse time-limit relay nearer the point of short circuit has not had time to function. To prevent this, the definite time-limit relays should be placed in the branch lines at a distance from the power station, and the inverse time-limit relays nearest to the power station.

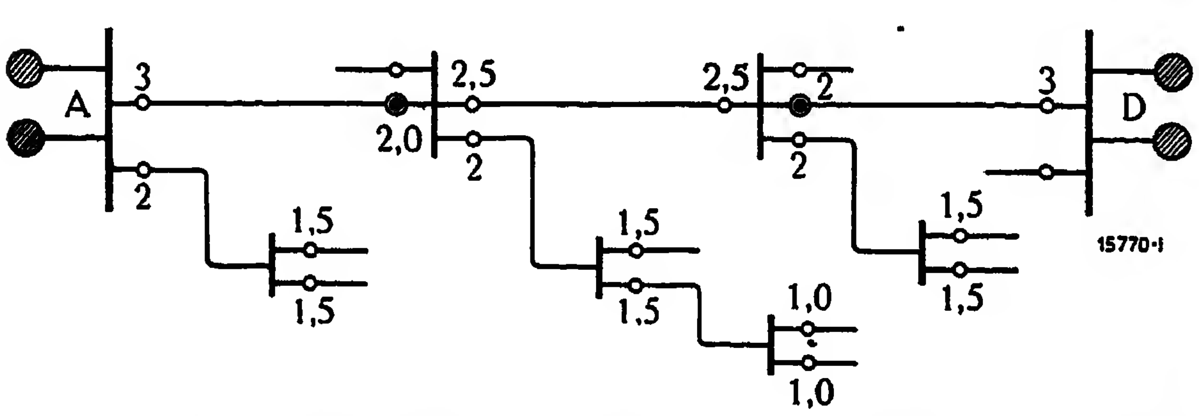


Fig. 32. — **Two power stations linked up by a sectionalised compensating line.**

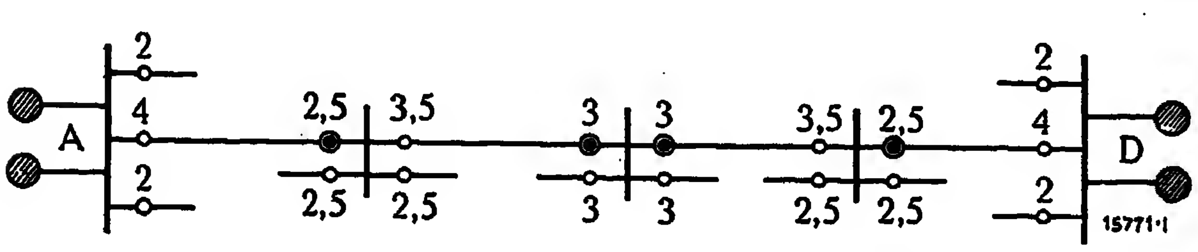


Fig. 33. — **Two power stations linked up by a sectionalised compensating line.**

4. Improvement of selective action by reverse-power relays.

If a subdivided line be fed from both ends, as is the case, for example, with the line connecting power stations A and D as shown in Figs. 32 and 33, it no longer suffices to place automatically tripping switches on one side of a branch point only, as shown in Fig. 24. Provision must be made for automatically isolating both ends of line sections. As, however, the longest admissible time lag as well as its finest practical graduation are given factors, and as the number of switches in series is now double what it was before, the extent of the selective system would have to be reduced to half the former number of line sections in series, if some other method were not applied. This method has been found in the principle of *counter time-lag graduation* combined with the use of the reverse-power relay.

This method consists in graduating for each power station the time lag of those relays only which are placed on the remote side of the branching points with regard to the station in question, but not the relays on the side of branching points nearest the station. In Figs. 32 and 33, the time lags resulting from this system are given in seconds. Further, each over-current relay, which is turned towards the power station when seen from the middle branching point or middle line section, is provided with a reverse-power relay acting as a blocking relay (double circles in Figs. 32 and 33). The contacts of the latter are in series with those of the over-current relays and are normally closed (opening contacts). The reverse-power relay of normal design (see pages 8 and 9 and also Fig. 35) is so set that its contacts open and prevent the tripping of the corresponding switch when the current flows towards the branching station. The con-

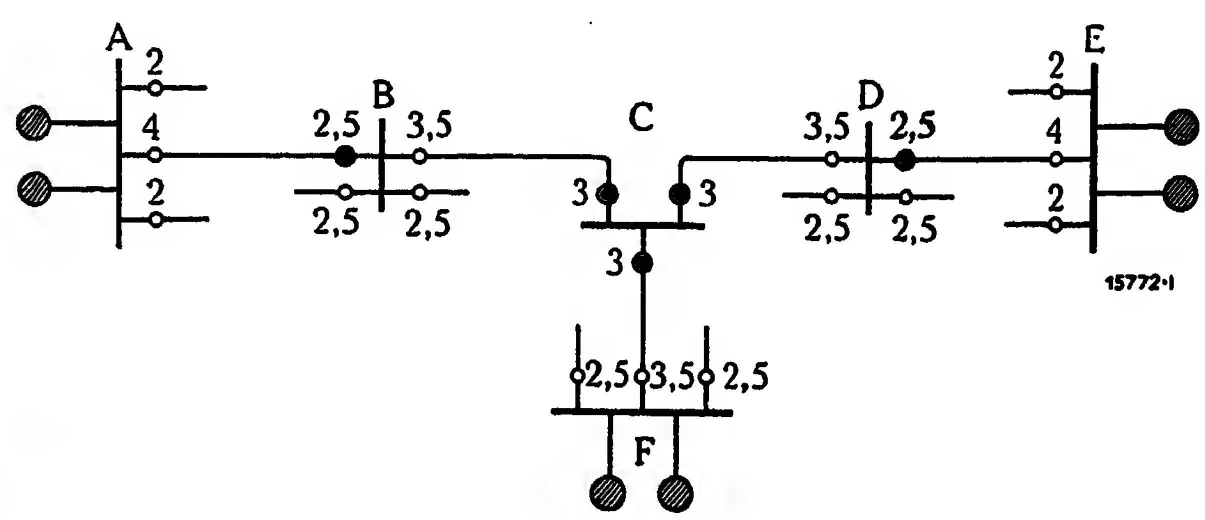


Fig. 34. — **Two power stations linked up by a sectionalised compensating line.**

tacts are held closed and leave the over-current relay free to act and trip the switch when the current flows out from the branching station.

In the systems reproduced diagrammatically in the figures, a branch line is shown at each branching station, and the longest admissible time lag of the over-current relay on the switch at the beginning of this line is given. If now the branch line be again subdivided into several sections or branches, each successive relay must be given a time setting one step lower.

Whatever the point on the system at which the short circuit takes place, the resulting current flowing from the station towards that point will have such a blocking effect that, of all the over-current relays through which short-circuit current is passing and which are free to act, those adjacent to the defective line section will have the shortest time lag. Thus the supply of all the other branches will continue undisturbed.

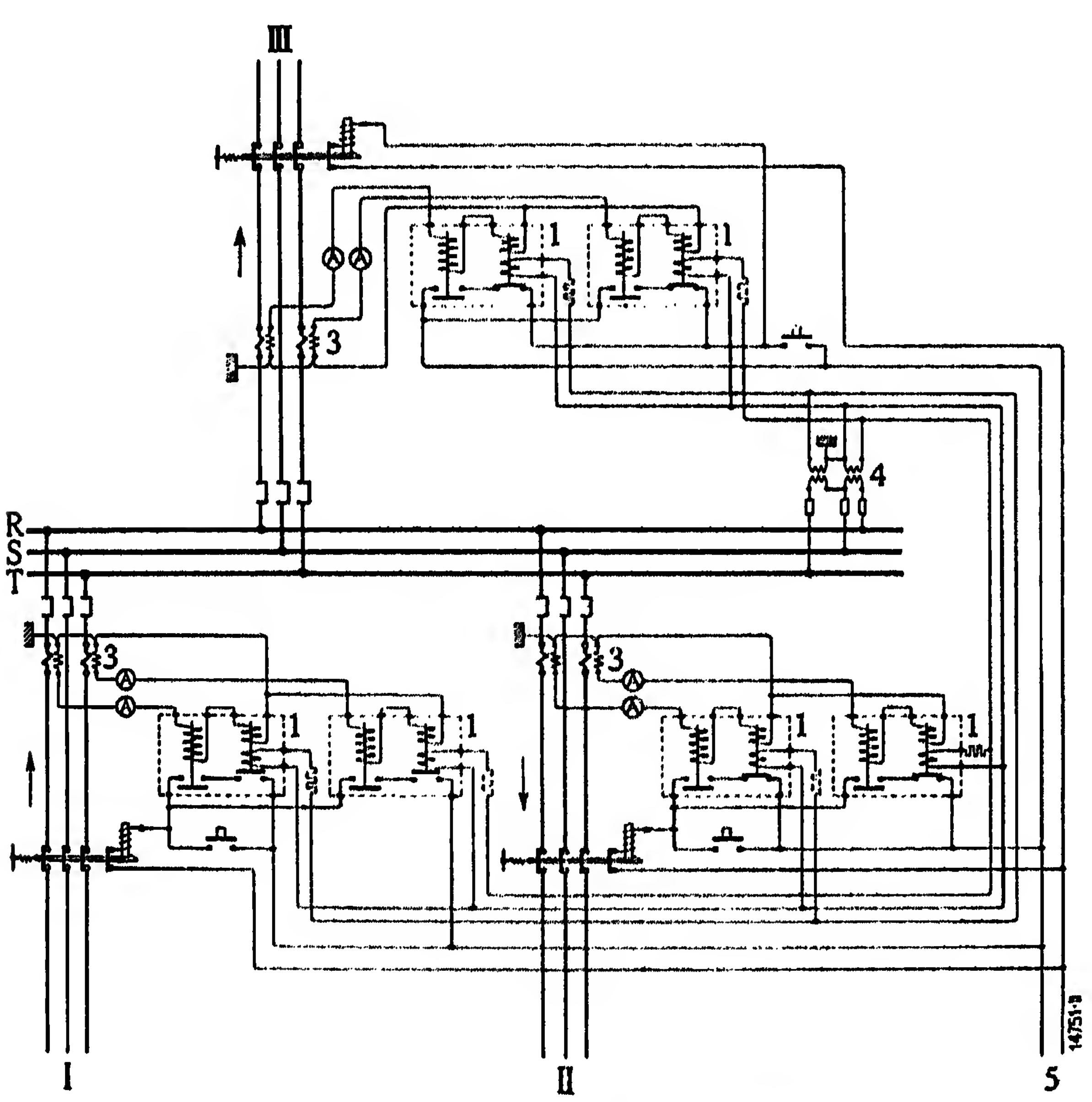


Fig. 35. — Selective protection of a branching station with changing sense of energy flow.

As mentioned on pages 14 and 15, the use of inverse relays calls for slightly less exactitude in setting.

If the connecting line be supplied with current not only from both ends but from a third or fourth power station connected to any branching station (Fig. 34), the principle set out above holds good. It is then only necessary that there should be counter time-lag graduation between all the power stations.

Fig. 35 shows the complete diagram of connections for two-pole selective protection of a three-line branching station suitable for energy flow in any direction, as is the case for branching station C in Fig. 34. The indicated position of the relay contacts corresponds to the sense of current flow shown by the arrows. According to the latter, the energy from line section I (BC) is taken as flowing away to, and over sections II (CD) and III (CF).

The selective protection of a system comprising single lines connecting several power stations by a common or branched line, but not by a ring or closed circuit, can be carried out by means of counter graduation of the time lags of the relays.

If now, the lines are composed of 2 conductors in parallel, it is still possible to obtain selective protection by the simple means decribed, when the short circuit occurs at about the middle of a line section, so that both ends are at about the same pressure, as the parallel line carries little or no current under these conditions. Selective operation of the switches may be hindered by the fact that the current in the undamaged parallel line changes its direction of flow according to the end of the section to which the disturbance is nearer, and that the value of this current can increase up to that in the damaged line. This difficulty is not overcome by any one of the so-called "cross differential connecting systems" put forward, such as "split-phase protection", etc. It is much better to allow, the undamaged line parallel to a defective section to be occasionally cut out together with that section, instead of trying to prevent this by complicating the system excessively.

With the above reservation, the counter graduation of the time lags is applicable to parallel connecting lines linking up two power

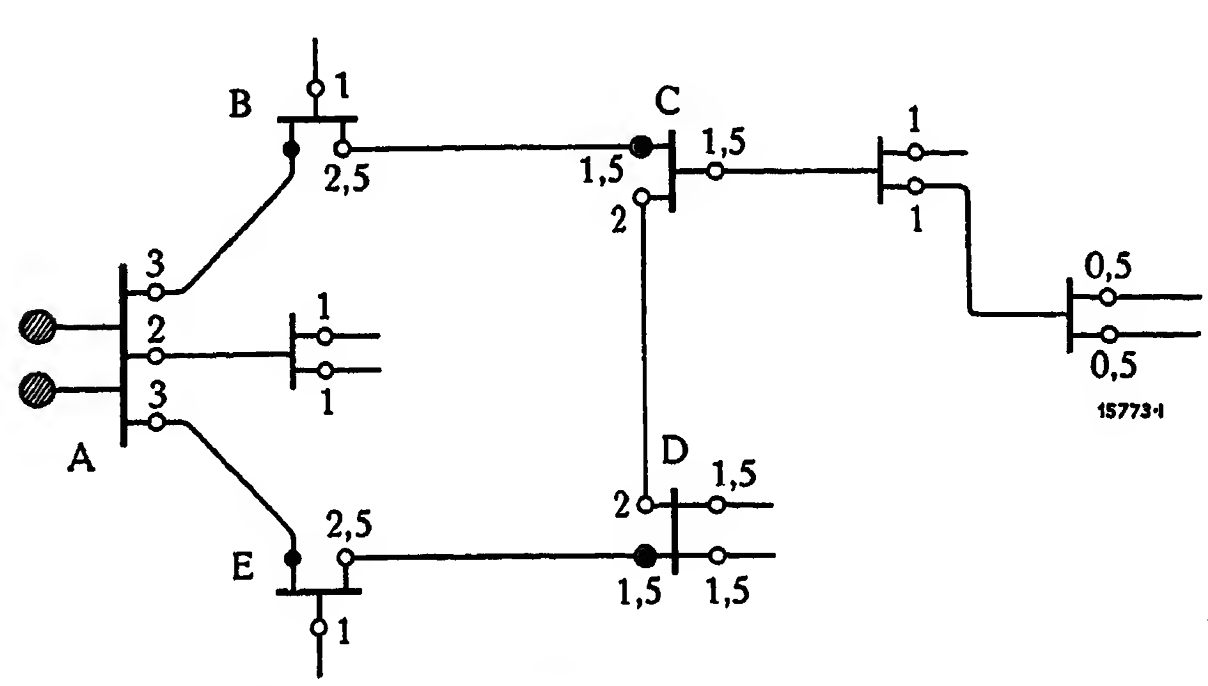


Fig. 36. — Ring system fed from one point.

stations. The setting of the time lag must be the same for both lines.

The greater the number of line sections, the longer must be the time setting of the switches at the power station.

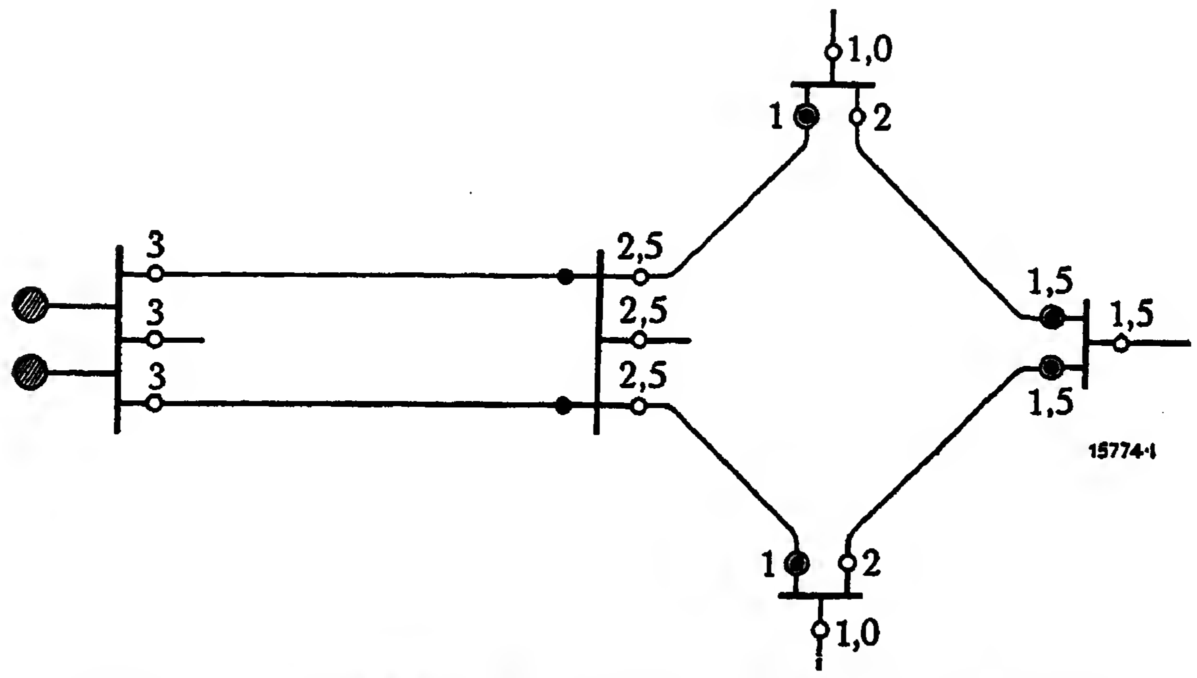


Fig. 37. — Ring system fed by double lines from one point.

The arrangements just described for selective protection with reverse-power relays and counter time-limit graduation are also suitable for ring systems fed from one point (Fig. 36) in which the short-circuit energy flows to the defective point, partly over B and partly over E. When the ring is always fed from the same point, all switches do not require to be provided with blocking reverse-power relays; it is sufficient to provide these at the ends of the line sections going out directly from the power station. When the ring is connected to the power station by one single or double line section, the diagram of connections is that shown in Fig. 37. There are often so-called diagonal lines, fed from the power station itself or from one of the first branching stations and supplying the principal centres of distribution; Figs. 38, 39 and 40 show lines of this kind. If the settings of the time lags on these diagonal lines be made to suit

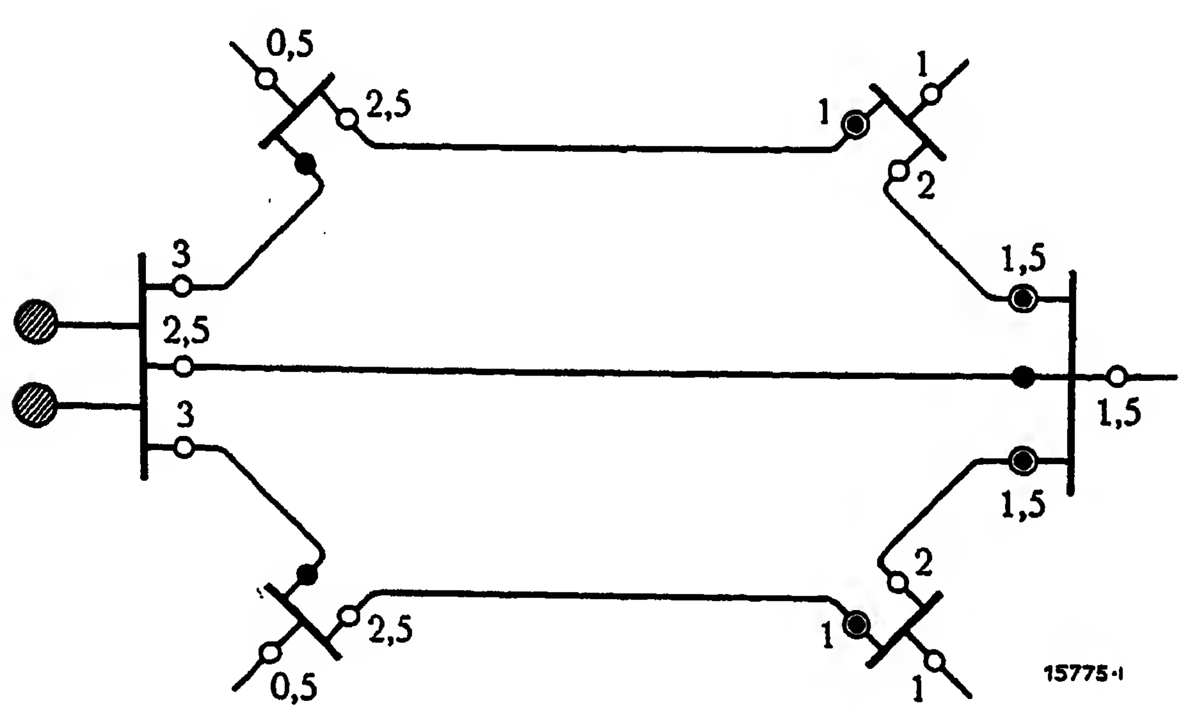


Fig. 38 — Ring system with a diagonal line fed from one point.

those of the ring relays, the selective protection of the system is not undueIy influenced by them.

Ring systems of all kinds supplied with current from one side only, with or without diagonal lines, can, therefore, be protected according to

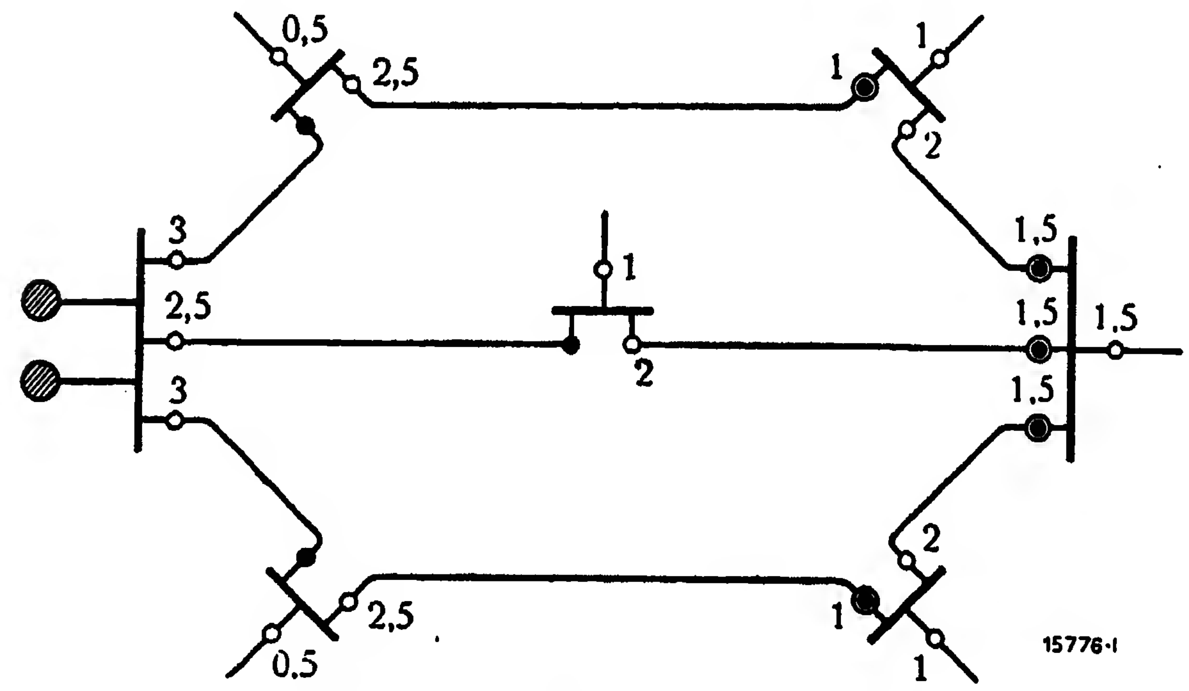


Fig. 39. — Ring system with sectionalised diagonal line fed from one point.

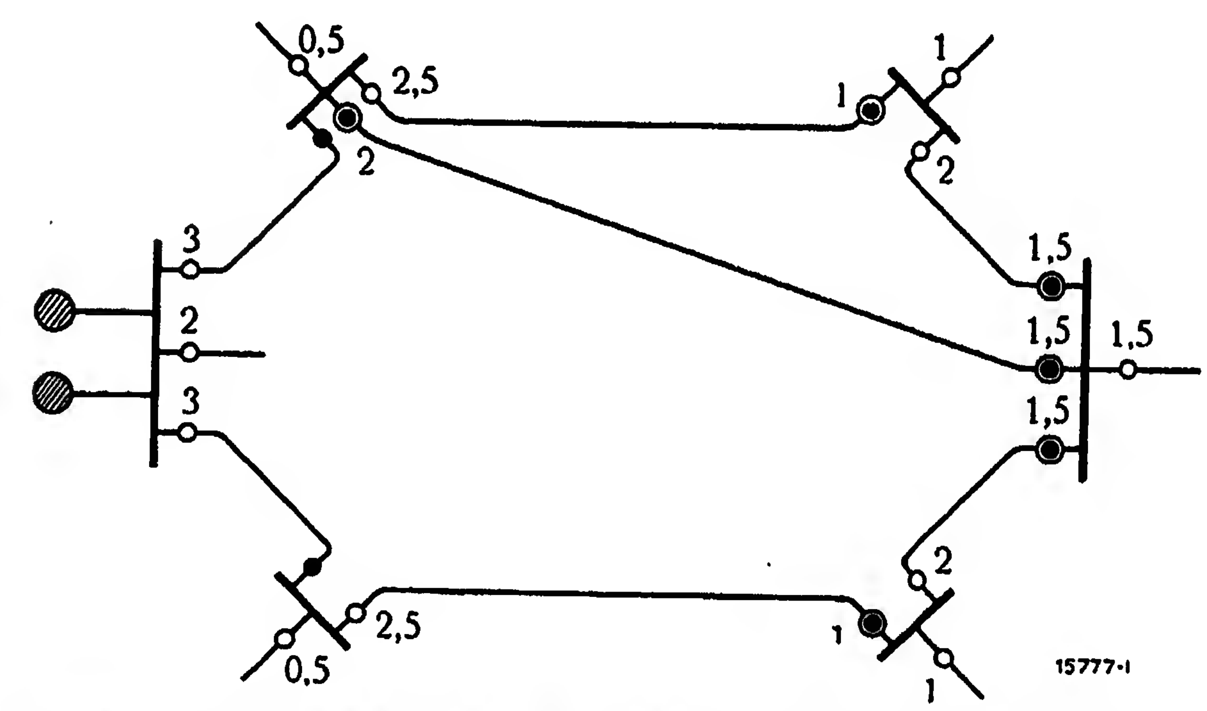


Fig. 40. — Ring system with asymmetrical diagonal line, fed from one point.

the principle of counter time-lag graduation if the line sections be composed of single conductors and not of several conductors in parallel.

Ring systems supplied with current from two or more points can also be protected by the simple selective device described, when the inner section (base line) lying between the two extreme supplying points is composed of a small number of line sections and only constitutes a fraction of the total resistance of the other parts of the ring. The time lags of the relays on the outer ring sections and branch lines must be shorter than those of the relays on the base line. If the resistance of the base line ABC in Fig. 41 be too great compared with that of the outer ring sections CDEFA, a short circuit occurring near A—B would cause too much current

to flow in the outer ring so that it would be cut out before the defective section itself A—B. Diagonal lines through the ring exercise an undesirable influence on the resistance conditions and may easily cause undue tripping of switches. When inverse time-limit

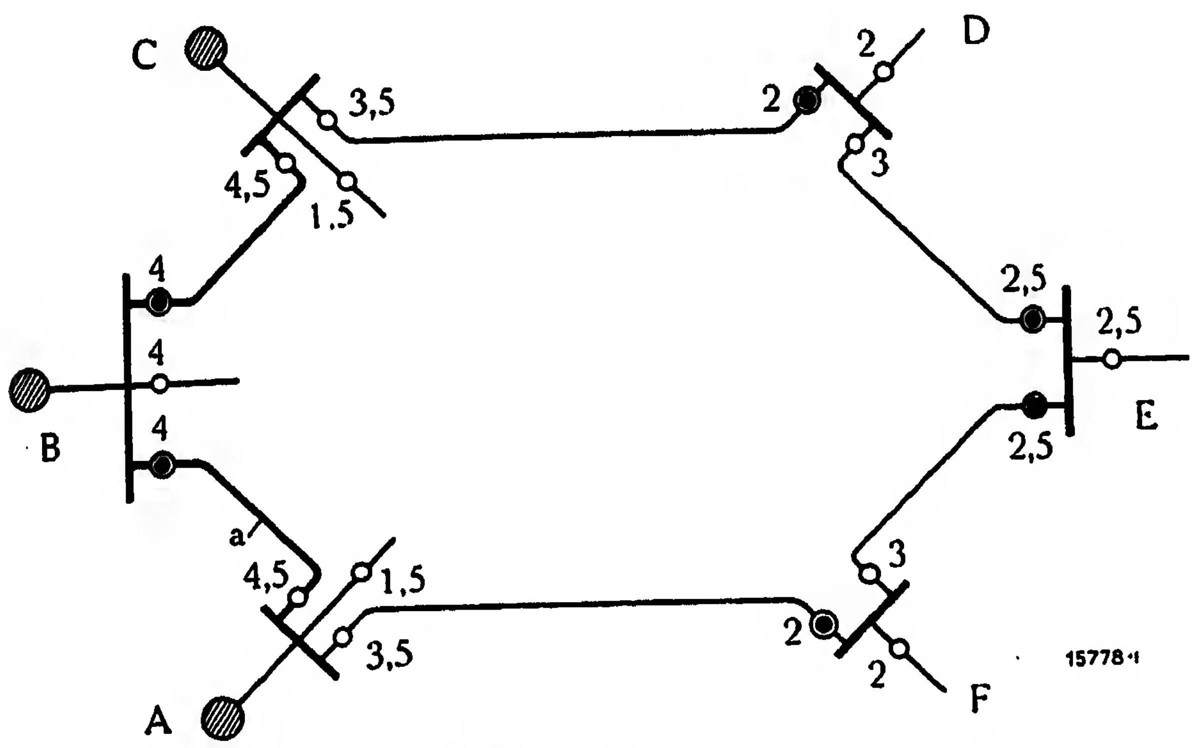


Fig. 41. — Ring system fed from several points.

over-current relays are used, it is not necessary that there should be so big a difference between the conductor resistances of the base line and outer ring, because these relays require a longer time to trip, especially when the short-circuit currents are small.

If, therefore, a ring system supplied from two or more points is to be protected by counter graduation of the time lags, the base line must be as short as possible and have a much smaller resistance than that of the outer ring section. Diagonal lines are to be avoided and the use of inverse time-limit relays is to be recommended.

The observations made on page 17 also apply, and in the same sense, for ring systems composed of two parallel conductors. Apart from cases where short circuits take place at the ends of the line sections, selective protection by counter graduation of time lags can be applied to these systems.

5. *Other methods of selective protection.*

In ring systems supplied from several widely separated points, and in systems, the diagrams of connection of which cannot be brought into line with any of the normal types by the opening of suitable switches, the service engineer is faced with the alternative of either reckoning with the undesirable tripping of a switch from time to time, or else of using more complicated methods of protection, such as the differential-current tripping devices some times used in England and America. In this latter protective system, when a defect occurs, relays are made to act through the agency of specially designed current transformers fed by pilot wires along the lines. The application of these differential connections to new cable systems is a relatively simple matter, because the auxiliary wires can either be placed inside the main cable or laid with it. With existing systems, however, and especially overhead high-tension lines, these methods can hardly be considered owing to their high cost of installation. They are least suitable of all for high-pressure plants, although this is the case where the need for such protection is greatest, because the current transformers mounted on the bushings of the switches are not sufficient for the special demands made on them and must be replaced by special current transformers, which is impracticable owing to the heavy costs entailed.

A somewhat more promising field of application seems to be open to the attempts made to obtain complete selection with the aid of the pressure drop in the line, the amount of which denotes the distances of the defective point from the power station. The solutions so far based on this principle, however, seem to have been only partly successful, because, it has never been frankly admitted that a satisfactory solution of the problem is only possible if an overcurrent time-limit relay, a directional relay, and some form of apparatus influenced by the pressure are employed. Further, no apparatus dependent upon the pressure has so far been evolved with a sufficiently strong differential action on the tripping time when subjected to the low pressures in the immediate neighbourhood of the short-circuit point.

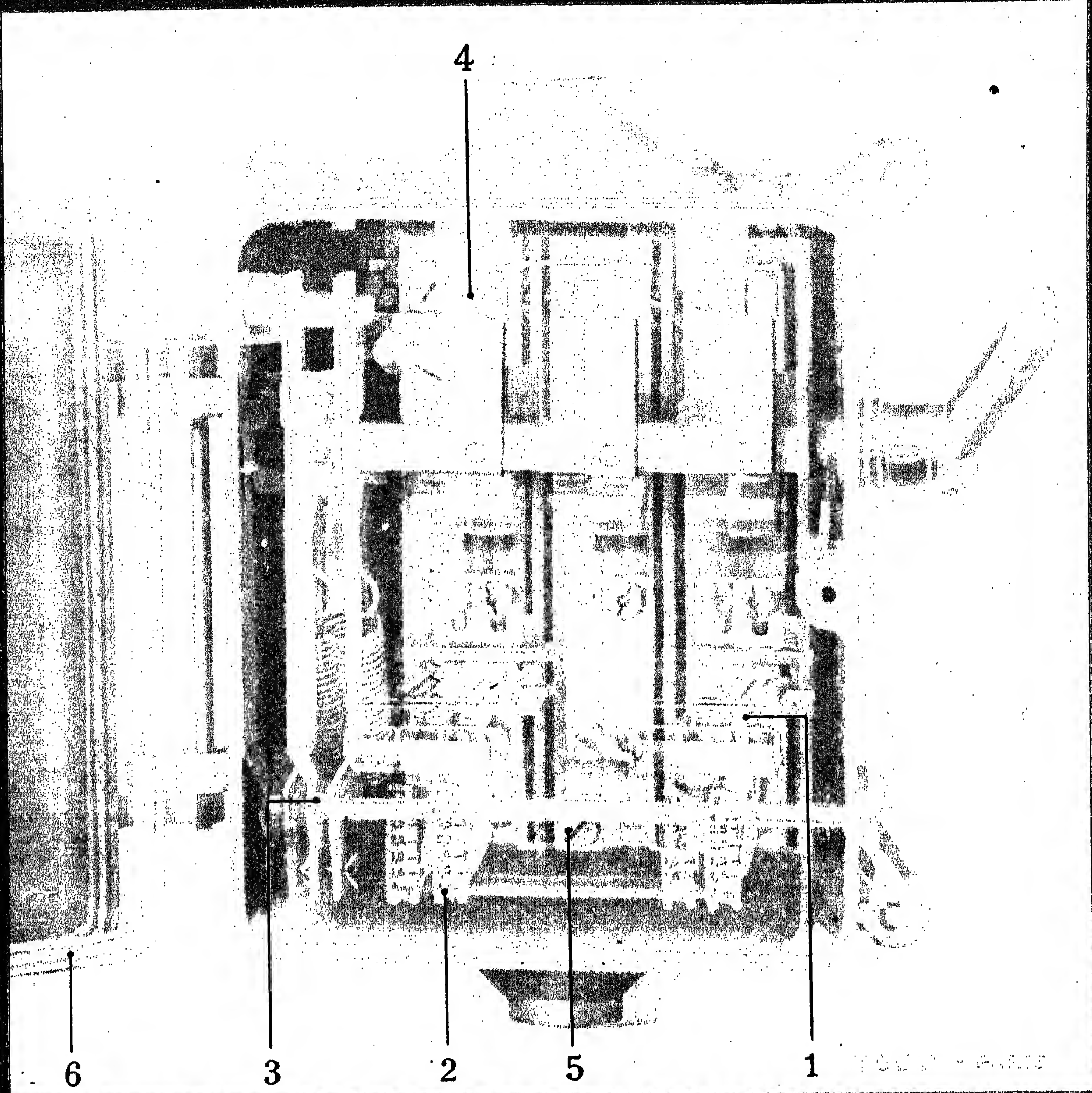
A system for the selective automatic cutting out of defective sections of the more complicated networks, in a manner both sufficiently simple for practical use and reliable in operation still remains to be found.

H. E. Frey. (C. M.)

Perfect protection for electric motors

Simple

Safe



Cheap

Approved

This frontispiece should be viewed through the glasses provided

SWITCHBOXES TYPE L

WITH

COMPOUND STRIP TEMPERATURE RELEASE

BROWN, BOVERI & COMPANY
LIMITED
BADEN (Switzerland)

875 E — XI. 7
(1244)

April, 1926

Motor Protection depends upon preventing excessive overheating.

Fuses cannot perform this task with entire satisfaction. When chosen to suit the normal current of the motor, their small carrying capacity causes them to blow frequently under overloads which could be withstood by the motor with perfect safety. **Interruptions in service are thus frequent occurrences.**

On the other hand, the high starting current of all squirrel-cage motors and many types of slip-ring motors, added to the fear of shut-downs, practically compels the choice of heavier fuses. These only afford protection against short circuits and heavy overloads and are of no avail with moderate overloads which may yet be sufficient to cause damage. **This leads to burn-outs and costly repairs.**

A further danger often encountered is the blowing of a **single** fuse on a three-phase motor and its continued operation on one phase.

Thus fuses waste both time and money.

Overload relays, although better than fuses, have the same disadvantage of only coming into action at a definite overload. The usual range of adjustment is from 1·4 times to twice the full-load current which offers no safeguard against the motor being burnt out by a continuous though moderate overload.

Complete protection is only afforded by an apparatus in which the conversion of the load fluctuations into temperature fluctuations follows the same law as in the machine to be protected.

This is accomplished in the most ideal manner by the Brown Boveri

Compound Strip Temperature Release

which is protected by patents in the majority of countries. The compound strip is formed by welding together two metal plates having different coefficients of expansion. Such an element bends when heated owing to the unequal expansion of its parts. By a suitable choice of materials and the combination of different elements to form a compound strip, it is possible to obtain quite large deflections, producing forces which can be **directly utilised for tripping switches.**

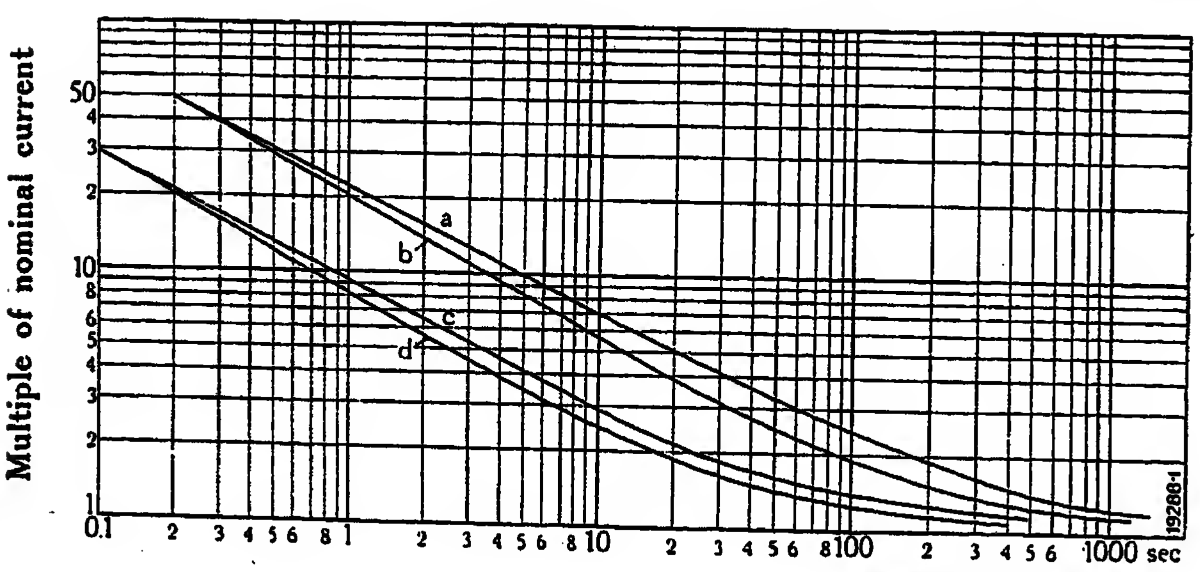


Fig. 1. Overload-time curves

1. **Motor:** for an excess temperature of approximately 75° C in the copper of the winding. Curve a, from 0° C excess temperature; curve c, from 60° C excess temperature.
2. **Release:**
   Curve b, from 0° C excess temperature; curve d, in conjunction with a continuous load with the nominal motor current.

Such compound strips, mounted in a cast-iron switchbox have approximately **the same characteristic heating curve as the electric motor itself, whether starting from cold or after previous heating. This is true for the whole range from one to fifty times the rated current.** The curves a, b, c and d in Fig. 1 show this extraordinary similarity and also make it clear that when using the compound strip temperature release **no special overload and short-circuit protection** is necessary as is the case with all other thermal protective devices.

The compound strip temperature releases are manufactured in ten types for switchboxes type L, graded from 1 to 100 A according to a geometrical series (Fig. 2). They can be readily interchanged should the switchbox be used under new conditions for which the original release was not suitable.

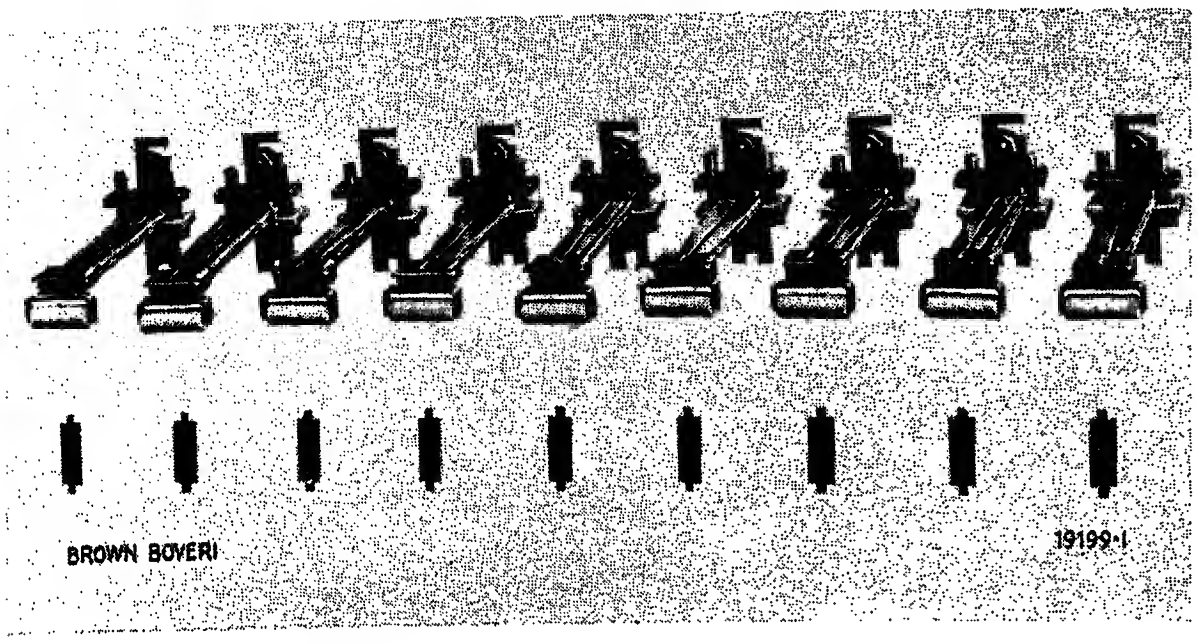


Fig. 2. Compound strip temperature release elements.

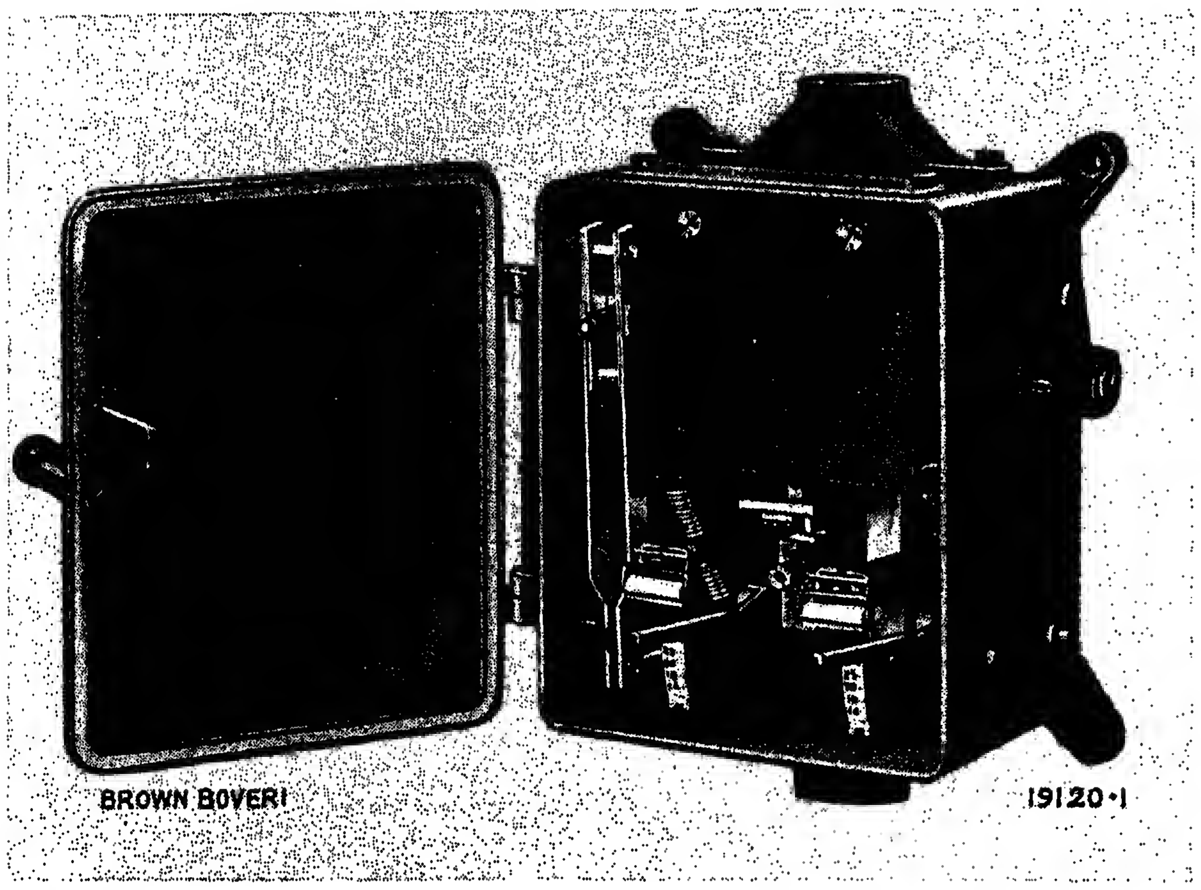


Fig. 3. Switchbox Type L, open.

Figs. 3 and 4, as well as the frontispiece, show the switchbox type L. These are designed for a pressure of 660 V and a rated current of 64 A, and may be used for three-phase motors of from 0·5 to 75 H.P., according to the working voltage and type of motor. The breaking capacity is 250 kVA. An **ammeter** and a **no-volt release** can be fitted if desired.

The principle of action of the compound strip temperature release will be seen from the frontispiece. The **compound strip 1** bends downwards under the influence of the heat produced, the deflection being proportional to the rate of increase of the current flowing. This movement is transmitted by the **tripping current adjusting device 2** to a **catch 3** which releases the spring-controlled spindle of the switch. The adjusting device permits fine adjustment of the tripping current. The switch may be closed quite soon after it has tripped, only a short cooling period being necessary. The adjustment can be made with perfect safety while the cover is open, since an interlock prevents the cover being opened until the switch is off.

The **extreme simplicity and accessibility** of the apparatus will be apparent from Figs. 3 and 4 and the frontispiece.

Switchboxes type L are necessarily somewhat more expensive than corresponding switchboxes with fuses, but the **extra cost is soon repaid by the saving on fuses, repairs, time and trouble.**

P. T. O.

Fig. 4. Switchbox, Type L, with ammeter.

Advantages of the Switchbox Itself.

Accurately suited to the characteristics of the motor.

Adjustable to any desired tripping current.

Direct tripping.

Maximum simplicity.

Low price.

Advantages of Using the Switchbox.

Satisfactory protection of the motor against dangerous overheating, by reason of the similar temperature characteristics of the compound strip.

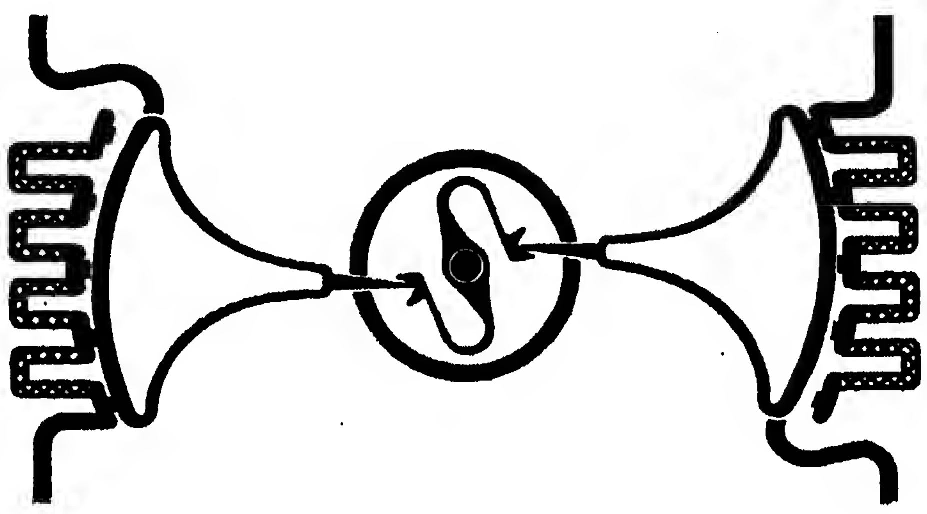
Protection against short circuits and running on one phase.

Hence few repairs, reduced maintenance, lower running costs.

Insensitiveness to safe overloads, and hence no unnecessary shut downs.

Fullest utilisation of the motor without attendant risk, hence high efficiency and improved power factor.

AUTOMATIC PARALLELING OF SYNCHRONOUS MACHINES AND OF ELECTRIC POWER PLANTS



BROWN, BOVERI & CO.

BADEN (SWITZERLAND)

785 E

March, 1923

AUTOMATIC PARALLELING OF SYNCHRONOUS MACHINES AND OF ELECTRIC POWER PLANTS.

Decimal index 621. 312. 005.

INTRODUCTION.

OWING to the present economic conditions, it is more necessary to-day than ever before, to limit to the strictest minimum, all running expenses in electric power plants. It is, therefore, not surprising that the demand for automatic apparatus, by which saving can be effected, has increased considerably since the beginning of the crisis through which we are passing. The use of automatic pressure regulators, protective gear and starting-up devices not only results in a considerable reduction in the number of attendants necessary for running the plant, but also saves the machines and apparatus from severe strains, by making faulty switching impossible, the great decrease in overhaul and replacement costs being immediately felt.

The Brown Boveri automatic synchroniser is typical of such apparatus in the saving which results from its employment and, although it has been but a short time on the market, it is now in very general use. Its object is the paralleling of synchronous machines, which operation it performs with a precision and speed quite impossible with ordinary synchronising gear. As, with this apparatus, the oil switch of the machine being synchronised closes automatically at the most favourable moment, it is impossible for even an inexperienced operator to make a faulty synchronisation.

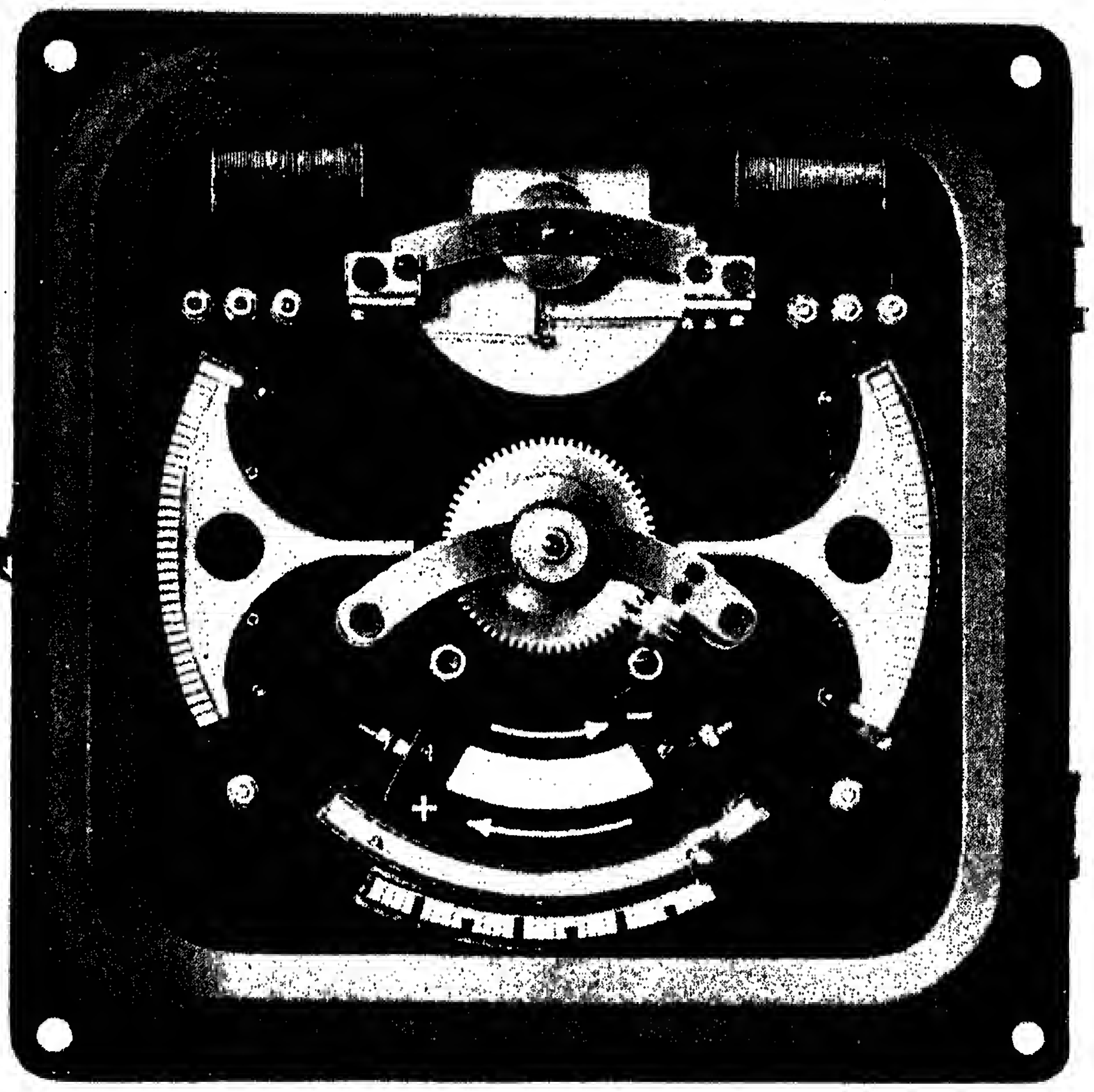


Fig. 1. — Automatic synchroniser, type P 2/1.

OPERATION.

The automatic synchroniser is connected up to the two separate pressures, namely, those of the two sets being synchronised, in the same way as with synchronising lamps and other devices for this purpose (see Fig. 3). The apparatus combines two distinct devices:

(a) *The time-lag relay* with a contact which, when closed, puts the remote control of the oil switch into action.

(b) *The regulating device* which imparts to the working of the relay its characteristic.

The time-lag relay (see Fig. 2) works on the Ferraris principle and comprises an aluminium disc the steel spindle of which is mounted in jeweled pivots. When it rotates under the influence of the rotating field produced by the two electro-magnets, this disc winds up a thread the end of which is fastened to a contact carried on a spring. If the coils of the electro-magnet remain under pressure sufficiently long to allow the disc to wind up the full length of thread, the contact will be closed and the circuit over terminals 9 and 10 will be completed. By means of an intermediate relay which energises the remote control of the oil switch, the latter is closed and the machine in question is thus paralleled.

The coils of the time-lag relay are connected up to the two separate pressures in such a manner that, when the phases of two machines to be synchronised coincide, the total pressure across the ends of the coils is double the separate pressure of each machine (the same connections as with synchronising lamps arranged for coupling when alight.)

Fig. 4 is the diagram of pressure variation at the coil ends, and thus also the diagram of the current in the relay coils. This diagram is drawn up on the assumption that the individual frequencies of the two sets, which are at first divergent, gradually approach each other so that the interference period lasts longer and longer. The angular difference between the phases of the two sets is given in degrees on the horizontal axis. When the angular difference is 180°, the current is zero. It is maximum when the phase difference is zero, that is to say when both phases coincide, and falls to zero again when the angular difference once more is 180°. If now we assume the relay to be set for a current J_r, the aluminium disc begins to revolve whenever the current line intersects the line J_r, that is to say, at points c_1, c_2, c_3, c_4 of the interference periods. When the current falls and again intersects the line J_r at points d_1, d_2, d_3, the disc will stop. Then, under the influence of the contact spring, it will revolve in the contrary sense causing the thread to unwind.

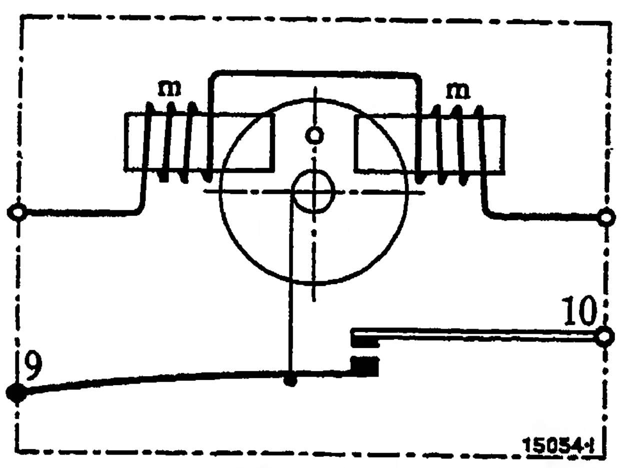


Fig. 2. — Time-limit relay of the automatic synchroniser.

In order to close the contact, the disc must continue to wind up the thread during a certain period represented by c a on the line J_r. This does not take place during the first three interference periods, because points a_1, a_2, and a_3, at which the contact might be closed, are beyond the current curve, in other words, the disc has already partly unwound the thread. Only during the fourth period, at the point a_4, is the thread completely wound up, making the contact, whereupon the remote control device begins to act and closes the oil switch at about the point b.

The two sets being now synchronised, the current which had fallen somewhat, immediately returns to its maximum value and remains thus until the automatic synchroniser, is disconnected by hand.

The examination of Fig. 4 shows that, under these circumstances, synchronising would not take place exactly at the moment when the current through the relay is at its maximum value, but only after some delay. Exchange currents would therefore be set up

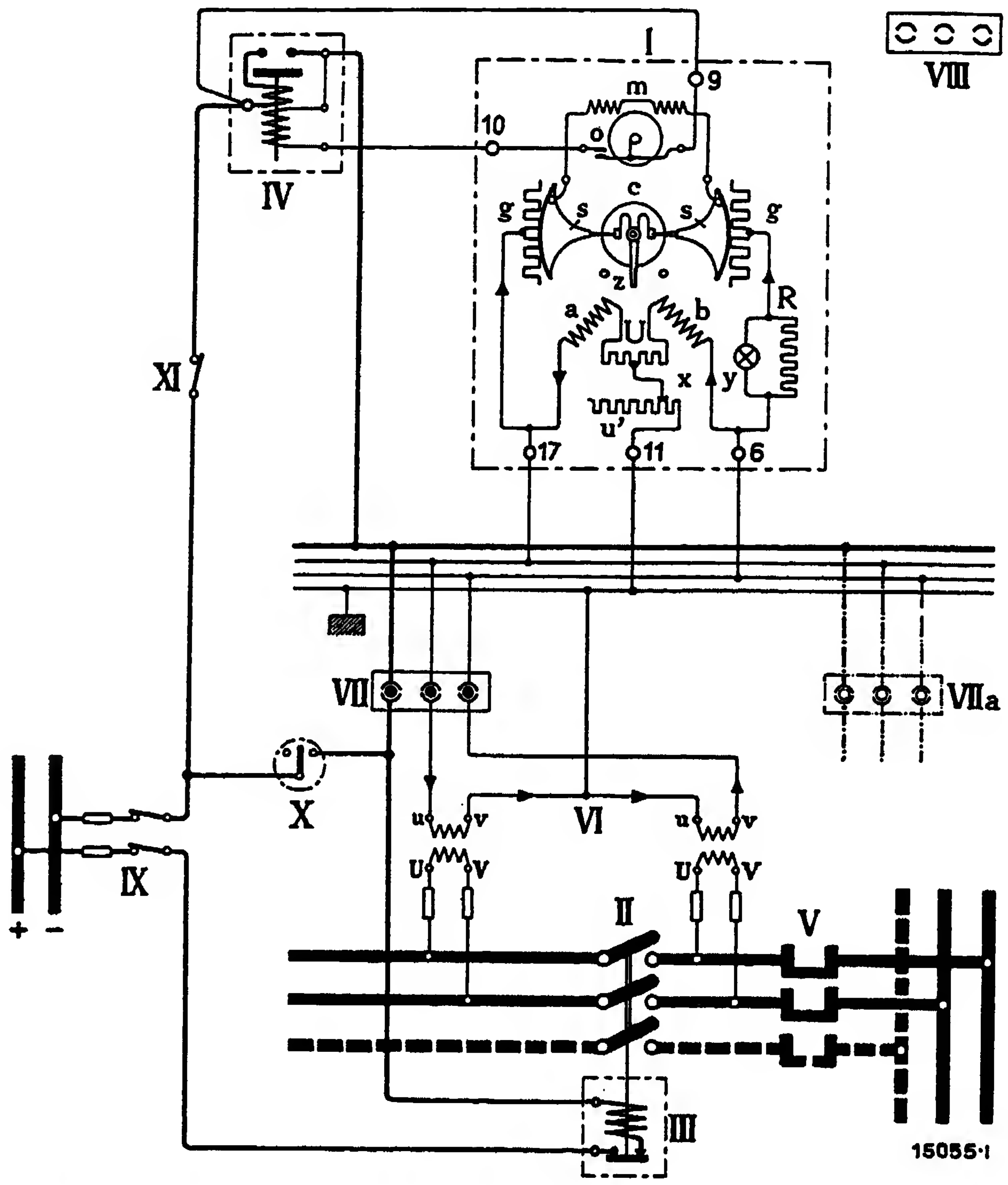


Fig. 3. — Diagram of connections of the automatic synchroniser for a three-phase plant (remote control with limit contact).

I. Automatic synchroniser.
II. Oil switch.
III. Remote control.
IV. Intermediate relay with holding coil.
V. Disconnecting switches.
VI. Pressure transformer.
VII & VIIa. Plug-type change-over switches for the different units.
VIII. Empty plug socket.
IX. Auxiliary-circuit switch.
X. Switch for hand operation of remote control.
XI. Intermediate-relay switch.

between the two sets, which might become considerable and endanger the plant.

The object of the regulating device is to eliminate this delay. For this purpose the coils of the

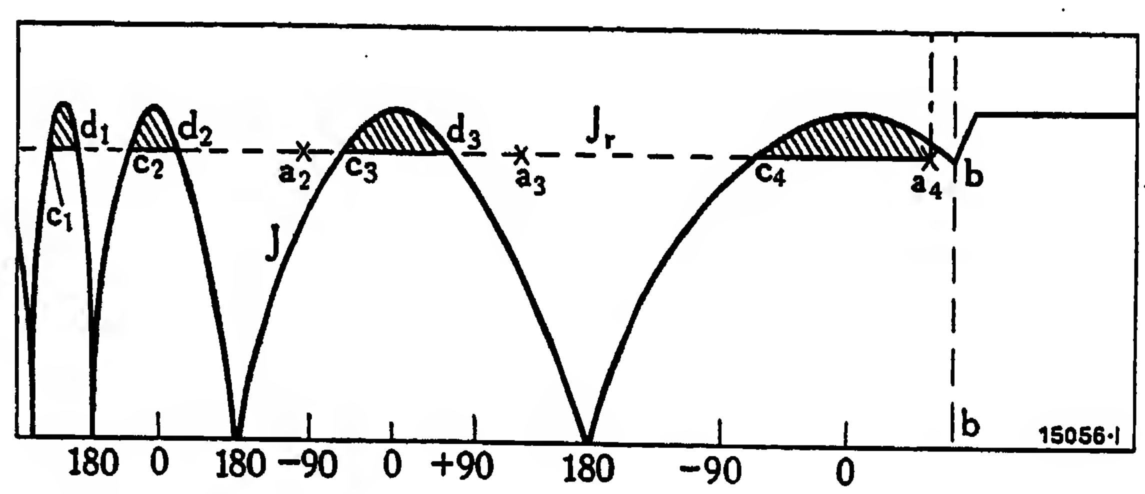


Fig. 4. — Diagram of current passing through the coils of the time-lag relay when the regulating device is not used.

J. Current curve.
J_r. Current value at which time-lag relay starts to act.
a. Moment at which the relay contact is closed.
b. Moment at which the oil switch is completely closed.

time-lag relay are not fed from the two individual pressures directly, but through regulating resistances g, which are composed of a number of resistance elements each connected up to a contact. These contacts form an arc of a circle on the grooved inner periphery of which the contact sectors roll. The steel point of the sector rests in a jewel bearing mounted on a spring, and is actuated by the rotating drum c so as to move through a corresponding arc of a circle, the point of contact between the sectors and the contacts being thus displaced.

This device is well known as it has been successfully used for a long time in the Brown Boveri automatic pressure regulator.

The rotation of the drum c is produced, according to the Ferraris principle, by the action of electro-magnets, the coils a and b of which are combined with the resistances U and u′ in such a manner as to produce a rotating magnetic field. The couple acting on the drum under the effect of this rotating field is zero when the phases of the two sets to be synchronised coincide. When, however, there is an angular difference between the phases, the drum revolves either in one sense or the other until it is brought up against the stops which limit its motion. The movement of the sectors causes a displacement of the point of contact, and thus a variation of the resistance inserted in the circuit of the time-lag relay. When the drum is in equilibrium in the mean position, that is to say, when the phases of the two sets coincide, the resistances g are short circuited and the time-lag relay is under the total pressure of the two units. When the drum is in any other position, a certain resistance is inserted in the circuit and absorbs a part

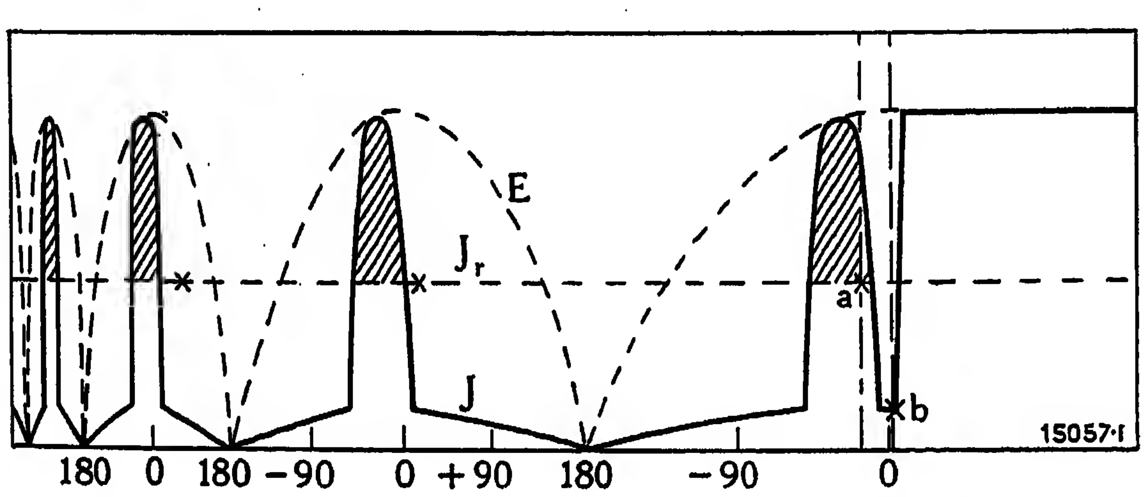


Fig. 5. — Diagram of current passing through the coils of the time-lag relay under the influence of the regulating device.

E. Curve of pressure across the terminals of the apparatus.
J. Current curve.
J_r. Current value at which time-lag relay starts to act.
a. Moment at which the relay contact is closed.
b. Moment at which the oil switch is completely closed.

of the pressure. Thus, when the drum reaches one of the limiting stops, the greater part of the pressure is absorbed in the resistances and the current passing through the coils of the relay is very weak. The diagram of Fig. 5 shows clearly the effect of this variable resistance on the relay current. If the relay be set to act under a current strength, J_r, the current through the relay will be much below J_r during the major part of the interference period; only when phase coincidence is approached will the current rise suddenly. At that instant the disc of the relay will be subject to a sudden impulse causing it to wind up the thread rapidly and to close the contact. It is evident that when the relay current varies as in Fig. 5, the relay operates with much greater precision than when the current curve has the form shown in Fig. 4.

The sector contacts and the rotating drum are not rigidly connected but are provided with a friction coupling. The angle through which the contact sectors can move is limited by stops as with the drum. The distance between the stops for the drum corresponds, however, to a bigger angular displacement than that of the stops for the contact sectors, so that, at every oscillation, the sectors are stopped before the drum. The couple under which the drum rotates is sufficient to overcome the friction of the coupling so that the drum continues its movement and an angular difference in the position of the contacts with relation to the drum results. This angular difference occurs in opposite directions according to whether the contacts have come up against the left or the right-hand limiting stop, but in both cases the displacement is such that when the contact point passes over the mean position again it is leading on the drum. The point of contact of the sectors will, therefore, reach the mean position before the phases of the two sets coincide and will therefore produce the short circuiting of the resistances g in advance.

This is clearly seen on Fig. 5, in which the maximum value of the current J is in advance of the maximum value of the pressure E. The practical result is obvious, namely, that the contact of the automatic synchroniser will cause the oil switch to close soon enough for the paralleling of the two sets to take place as closely as possible to phase coincidence, despite the lagging action of the remote control of the oil switch.

The distance between the stops and, therefore, the angular displacement can be so regulated that the delay in the action of the oil-switch remote control, which differs according to the kind of remote control in use, can be completely compensated.

An adjustable contact, which can be slid by hand along the contacts of the resistance u′ allows the torque on the drum to be varied so that the precision with which the apparatus operates can be increased or diminished considerably. If this contact be slid to its limit position on the left, synchronising is not rigorously correct but has the advantage of taking place very quickly. This is absolutely necessary when the system in question is subject to sudden and heavy load fluctuations, because in such cases the two frequences vary so much that it would be impossible to keep them equal, even during a short time.

On the other hand, the further the contact is slid to the right, the greater becomes the precision of the apparatus. It is necessary, in this case, to have more uniformity between the two frequencies in order to synchronise the machine.

This adjusting device permits of adapting the apparatus to the particular requirements of the plant to which it is applied, that is, to effect paralleling within a reasonably short synchronising period, consistent with the two frequencies coinciding as well as possible. The setting is made, once for all, when the apparatus is first put into operation, and a pin is provided permitting the case to be sealed or padlocked to prevent any alteration of this setting on the part of the attendants.

Mention must also be made of the *optical signal device*. This consists of an oscillating pointer and a lamp which lights up periodically. This device shows clearly if the speed of the unit to be connected in parallel with the busbars has to be increased or decreased. The apparatus can thus be used as a synchronoscope even when, for any reason, it is not desired to carry out synchronisation.

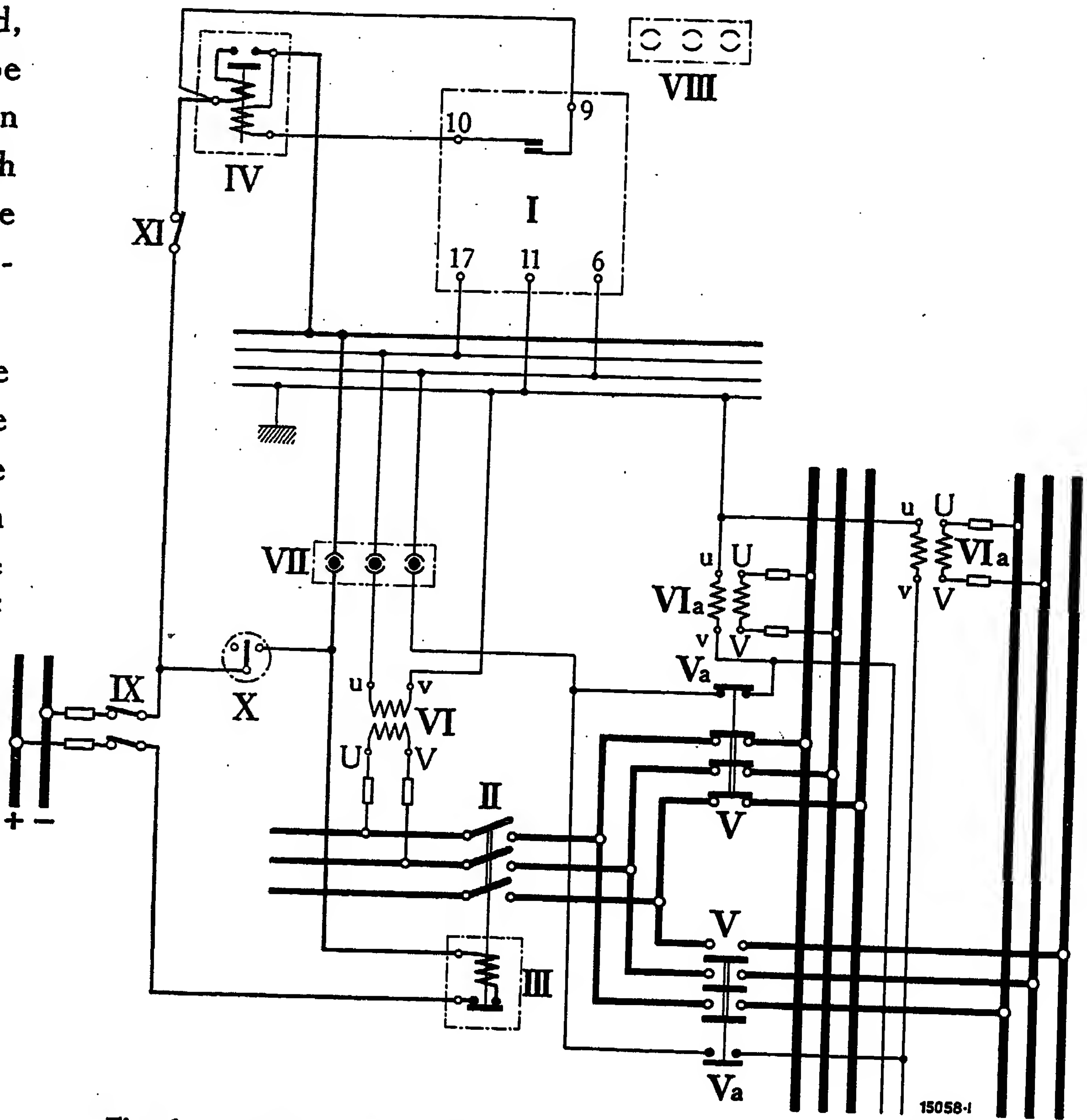


Fig. 6. — **Diagram of connections of the automatic synchroniser in a three-phase plant with several busbar systems (disconnecting switches fitted with a contact).**

I. Automatic synchroniser.
II. Oil switch.
III. Remote control.
IV. Intermediate relay with holding coil.
V. Disconnecting switches.
Va. Blocking contact.
VI. Alternator pressure transformer.
VIa. Busbar pressure transformer.
VII. Plug-type change-over switches for the different units.
VIII. Empty plug socket.
IX. Switch of the auxiliary circuit.
X. Two way switch for hand operation of remote control circuit.
XI. Switch for the intermediate relay.

PRACTICAL APPLICATIONS OF THE APPARATUS.

In a generating plant or a substation one automatic synchroniser alone is nearly always sufficient. In such cases, the apparatus is connected, as required, by means of plug-type change-over switches to the different units to be synchronised and to their respective oil switches. These change-over switches must always be arranged so that any faulty switching, on the part of the operator, does not lead to incorrect synchronising. It must not be forgotten that one of the principal advantages of the automatic synchroniser is to enable untrained operators to effect absolutely correct synchronisation.

No combination of transformers or switches which does not absolutely exclude all possibility of mistake may be taken into consideration at all. As an example of a dangerous arrangement, we would mention the use of pressure transformers connected to the busbars in plants where there are several sets of busbars operating independently. In such cases it is absolutely necessary that an interlocking device be used. This can be formed of auxiliary contacts mounted on the spindle of the disconnecting switches so that the automatic synchroniser can only be connected up to the pressure transformer of that busbar set on which the disconnecting switches are closed (see Fig. 6).

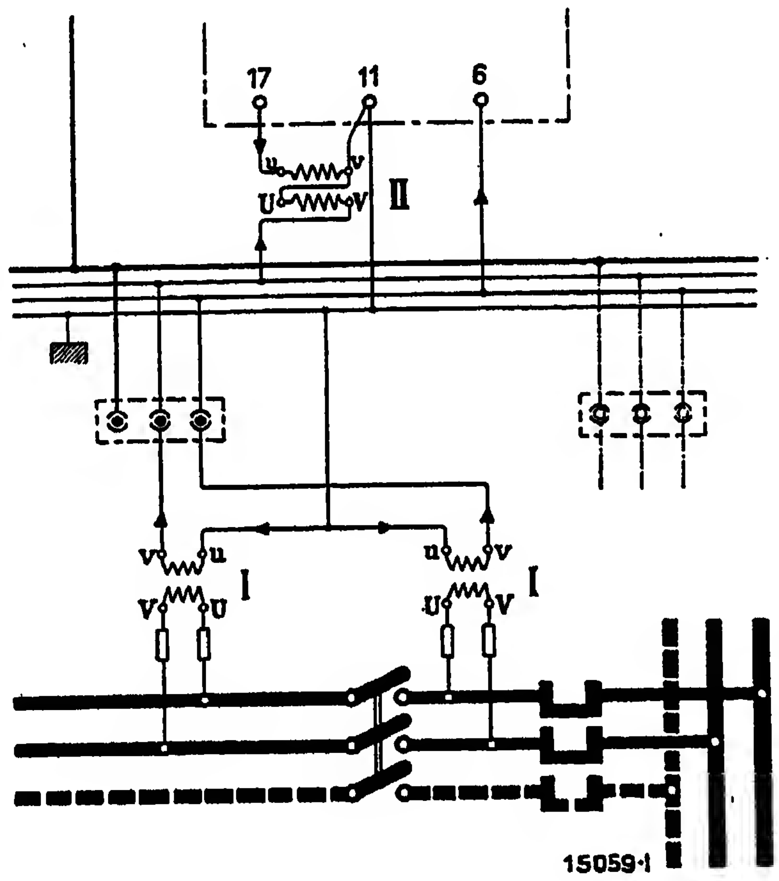


Fig. 7. — Connections of the inverting transformer for changing over from synchronism with dark lamps to synchronism with lighted lamps.

I. Existing pressure transformer.
II. Inverting transformer.

The safest and the simplest system of connections is that shown in Fig. 3. Two pressure transformers are used to feed the automatic synchroniser, and these are connected one on each side of the oil switch to be controlled. As it is always possible to use for feeding the automatic synchroniser, existing pressure transformers to which measuring instruments are connected, this arrangement does not always involve an increase in the number of transformers, provided the latter are fitted in accordance with the diagram, or can be changed over to agree with it. The connections are only made as shown in Fig. 6 in very rare cases where the arrangement of the transformers according to Fig. 3 is not possible without a big outlay.

In plants having one busbar system only, the busbar pressure transformer can always be used.

As said before, it is necessary that the pressure transformers feeding the apparatus be connected up so as to *light the lamps* when the phase coincides, that is to say, earthing must be carried out on the two transformers through opposite terminals. If, owing to existing apparatus, the earthing of the pressure transformers has already been made through the same terminal on both transformers (v and v, or u and u), synchronism will be obtained when the *lamps are dark* and a small inverting transformer (see Fig. 7) will have to be put in, in order to obtain synchronism with lighted lamps, as required by the apparatus.

A number of different types of remote-control device for the oil switch are to be found in practice. Certain of these have a limit contact which breaks the circuit of the switching-in coil of the oil switch when the latter is completely closed, others are without this device. In order to get good results with these different types of remote control, various arrangements of the automatic synchronising device itself have been studied. Figures 3 and 6 show the connections of the remote-control circuit when the oil switch is provided with a limit contact.

As the small contact of the automatic synchroniser cannot be called upon to switch off the current

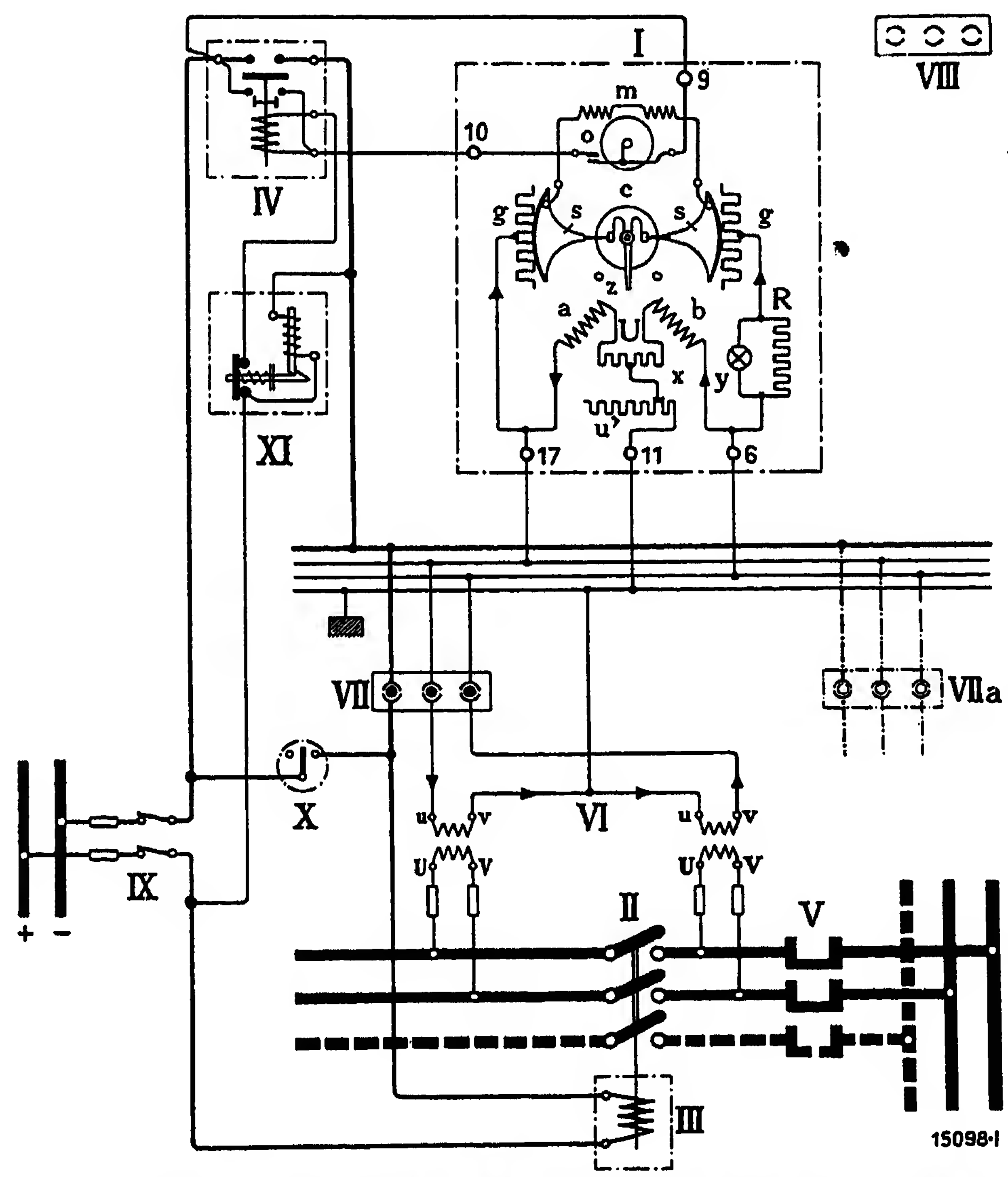


Fig. 8. — Diagram of connections of the automatic synchroniser in a three-phase plant (remote control without limit contact).

I. Automatic synchroniser.
II. Oil switch.
III. Remote control.
IV. Intermediate relay with auxiliary contact.
V. Disconnecting switches.
VI. Pressure transformer.
VII & VIIa. Plug-type change-over switches for the different units.
VIII. Empty plug soket.
X. Switch of the auxiliary circuit.
XI. Pushbutton switch with time-lag relay.

in the remote-control circuit, which current is generally very heavy, an intermediate relay IV is used, and this circuit is closed by the small contact of the synchroniser. The core of the relay is raised and closes the circuit of the switching-in coil of the remote-control circuit. At the same time, it short-circuits its own pressure coil and puts in circuit a holding coil, the winding of which is in series with that of the remote-control circuit. This holding coil keeps the contacts of the intermediate relay closed. After paralleling has been effected, the limit contact breaks the circuit of the switching-in coil of the remote control and therefore also of the holding coil, allowing the core of the intermediate relay to fall. The circuit of the pressure coil is also broken by the limit contact, so that, even if the contact of the synchroniser remains closed, the intermediate relay is not energised.

If this device were to be used for remote controls not having the limit contact described above, the switching-in coil would remain under pressure until the operator opened its circuit by pulling out plug VII. This coil is not wound to stand the switching-in current during any considerable period and, unless the circuit were opened very soon, it would heat up dangerously. It is therefore advantageous to use the arrangement shown in Fig. 8. The intermediate relay has no holding coil, in this case, but is only provided with a small auxiliary contact which holds the main contact closed when the pressure has been applied by the automatic synchroniser. A second relay XI. with a damping device, breaks the circuit of the intermediate relay coil, after a certain time lag. This causes the breaking of the current through the switching-in coil of the remote-control circuits. The lag can be set at will so as to give the remote-control gear sufficient time to close the oil switch completely. This arrangement has another advantage, namely, a catch for relay XI so that it can only be released by pressing a button. This button must be pressed to enable the next synchronising operation to be carried out. If the switching-in gear fails to function, owing to the oil switch or its remote control gear being out of order, a to-and-fro movement of the oil switch is avoided as the remote control is only actuated once.

GENERAL CONSTRUCTION OF THE APPARATUS

The automatic synchroniser, with the resistances belonging to the regulating device, forms a complete unit fitted in a casing which can be mounted on a switchboard. The contacts and the rotor are hermetically enclosed, the casing being provided with a glass front so that they are easily visible although well protected. The resistances, which are behind the casing, are protected by a perforated sheet-metal cover, which allows effective cooling. Wear is eliminated and the apparatus requires no more upkeep than any ordinary measuring instrument.

As the dimensions of the apparatus do not depend on the output of the sets to be synchronised, there is only one type built, which is wound for connection to alternating current at 2×110 volts. The intermediate relay can be supplied either for direct current or for alternating current, and in order to be able to calculate the coils, it is necessary to know the system and the pressure of the auxiliary source. For the devices shown in Figs. 3 and 6, it is necessary to know what current is absorbed by the switching-in coil of the remote control, so that the calculations necessary for the holding coil of the intermediate relay may be made.

H. C. Kloninger.

THE BROWN BOVERI SYSTEM OF AUTOMATIC CURRENT-LIMITING REGULATION.

Considering the remarkable progress made in the development of electricity supply in the last decade, and especially the extension of the network connecting super power stations all over the country, it is surprising to find that, in spite of the many safety devices now considered a necessary complement to every system of generation, transmission and distribution of power, whole systems are continually being disturbed by short circuits. The reason for this seems to be that the protective devices mostly used are not as efficient as is necessary for the increasing service difficulties.

Regarding these protective devices broadly, it appears that most of the systems now employed endeavour only to isolate faulty sections as quickly as possible. It is, of course, generally recognised that only such circuit breakers as are nearest the fault should open, to ensure that only the smallest possible portion of the system be cut out. To this end many ingenious devices have been placed on the market, some very good in particular services, others designed according to highly scientific principles, but results seem to show that more or less all of them lack to a certain extent the desirable qualities of reliability and simplicity. This is merely emphasised by the great number of different types and by the necessary special provision, in some cases of expensive cables, in others of pilot leads, and in almost all of exceedingly accurately adjusted transformers, which must have absolutely true ratio values.

Thus it is readily seen why a number of engineers responsible for the safety of a service, rather than rely on a series of complicated and highly sensitive protective devices, prefer to use alternators and distribution systems designed to be as far as possible short-circuit proof. Often choke coils are added, especially when stations are working in parallel, and by these means protective devices causing tripping of switches are reduced to a minimum, or even entirely dispensed with.

Complete protection, however, is not to be obtained by such means. Although choke coils greatly reduce the dangerous effects that can result from the instantaneous short-circuit current, there is still the probability of trouble arising from overheating, as, for example, if all the generators of one or of several stations supply current to a fault. Should this fault be a sustained one, much damage may be done. At first sight it would seem that there is no remedy and that either one has to chose a tripping device, or risk damage through overheating. There is, however, a very simple and efficient method of overcoming both these disadvantages, and that is the reduction of the excitation of all machines running while the short circuit lasts.

In power stations where a switchboard attendant is constantly on duty, it would be possible to arrange for the reduction of the excitation of the alternators by hand should the necessity arise, but in this case the safety of the plant depends upon the presence of mind of the attendant. Where the adoption of automatic quick-acting pressure regulators has enabled regular attendance to be dispensed with, the matter is not so simple, especially as such regulators automatically increase the excitation when the alternator pressure drops on the occurrence of a short circuit. This results in a still heavier short-circuit current and causes the lack of attendants to be felt very acutely. When the usual type of vibrating-contact voltage regulator is employed, the excitation is raised 30 or 40% above the value corresponding to full-load, and the danger of excessive heating is very great. For this reason, manufacturers of these regulators were led to provide a safety device, which puts them out of action when a short circuit arises, thus reducing the excitation below the value corresponding to no-load. While a device of this kind gives the protection desired, it has the disadvantage that, after the faulty part of the system has been isolated or the short-circuit arc extinguished, the pressure regulator must be set working again by hand, in order to restore the normal pressure.

It is no easy problem to design a universal protective device which will temporarily put the pressure regulator out of action while the fault is existent and then cause the pressure to attain automatically its normal value, as soon as the line is cleared. If an ordinary overload time limit relay is employed, hunting will arise between the relay and the voltage regulator necessitating the provision of a catch to hold the relay in the "off" position until it is released by hand. This device would certainly give a good protection against overheating of any parts of the plant through the sustained short-circuit current, but it would at the same time prevent normal excitation being automatically restored, i. e., breakdown of the service would not be prevented, and the main object of every protective device would not be attained.

The Brown Boveri automatic current-limiting regulator is an apparatus which completely fulfils the requirements demanded of a protective device for the purpose in question and whose reliability has been proved under the most severe and most diverse conditions. By reason of the powerful and stable way in which the current-limiting regulator acts, it co-operates excellently with the automatic pressure regulator, and hunting is entirely overcome. There is no chance of the working of the current-limiting regulator being influenced by the pressure regulator since the resistance that can still be cut out by the latter when a short circuit occurs is, in all cases, smaller than the value of the resistance still available in the current-limiting regulator; that is to say the normal floating position of the voltage regulator is such that the greater portion of its resistance is short-circuited, and the amount by which the excitation can be increased upon a pressure drop is comparatively small when compared with the action of the current-limiting regulator whose resistance is cut out for normal running, and is, therefore, all capable of being inserted should a rise of current occur.

THE BROWN BOVERI AUTOMATIC CURRENT-LIMITING REGULATOR.

The current-limiting regulator is an apparatus that does not differ very much, as regards general construction and appearance, from the well-known Brown Boveri automatic pressure regulator with rolling sectors and silver contact pieces. The motive system (Ferraris type) and the contact sectors, together with the segments upon which they roll, have been retained. Apart from the modified arrangement of connections and winding, the only difference of any importance between these two types of apparatus consists in the omission of magnetic damping from the current-limiting regulator, in order that it may operate as quickly and powerfully as possible.

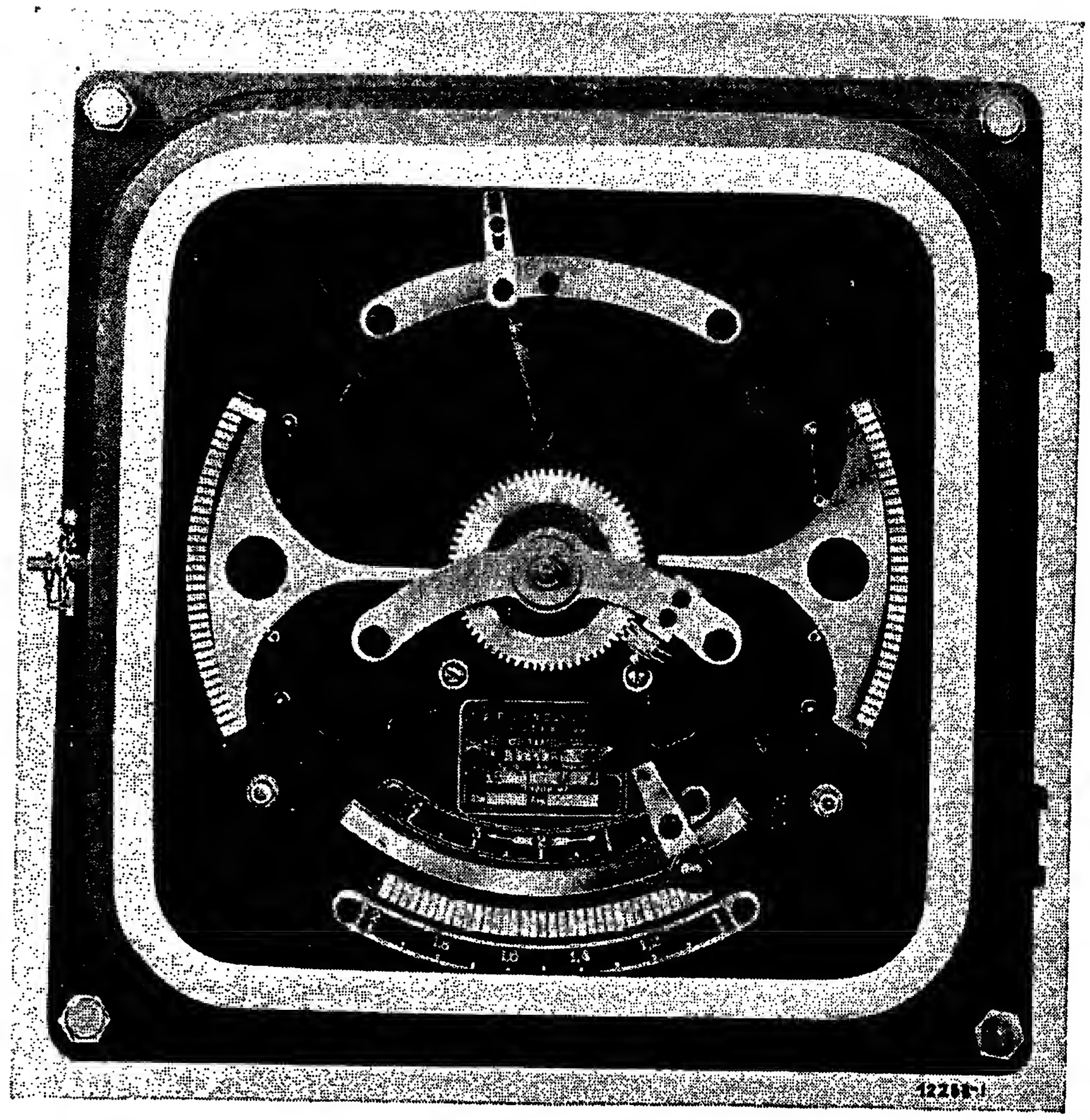


Fig. 1. — Brown Boveri automatic current-limiting regulator, Type A 2/1 (small model).

In three-phase plants the apparatus is connected to two current transformers having their secondary windings in parallel, but with the leads crossed for obtaining the so-called 60-degree coupling. Fig. 2 gives the connections for this arrangement, while Fig. 3 is the vector diagram in which the resultant current J is indicated. The way the regulator is connected ensures that it will operate not only with a three-phase short circuit but also with a fault between any two of the phases.

The ratio of transformation is so chosen that with full-load on the alternator the secondary current is 1 ampere. Consequently the value of the current in the windings of the current-limiting regulator is $1 \times \sqrt{3} = 1{\cdot}73$ amperes.

As with the pressure regulator, the electro-magnetic torque is opposed by that of the spring so that, as long as the action of the spring is the stronger, the rotor of the regulator rests against the right hand stop. The pointer is then on 0 (Fig. 4).

If, however, the current for which the regulator has been set is exceeded, the electro-magnetic torque overcomes that exerted by the spring and the rotor leaves the zero position. When the current increases further, the rotor comes right round until it meets the left-hand stop, where the pointer stands on 4.

The resistances are situated in the rear part of the apparatus itself, and are connected to the various steps of the contact segments. They are completely

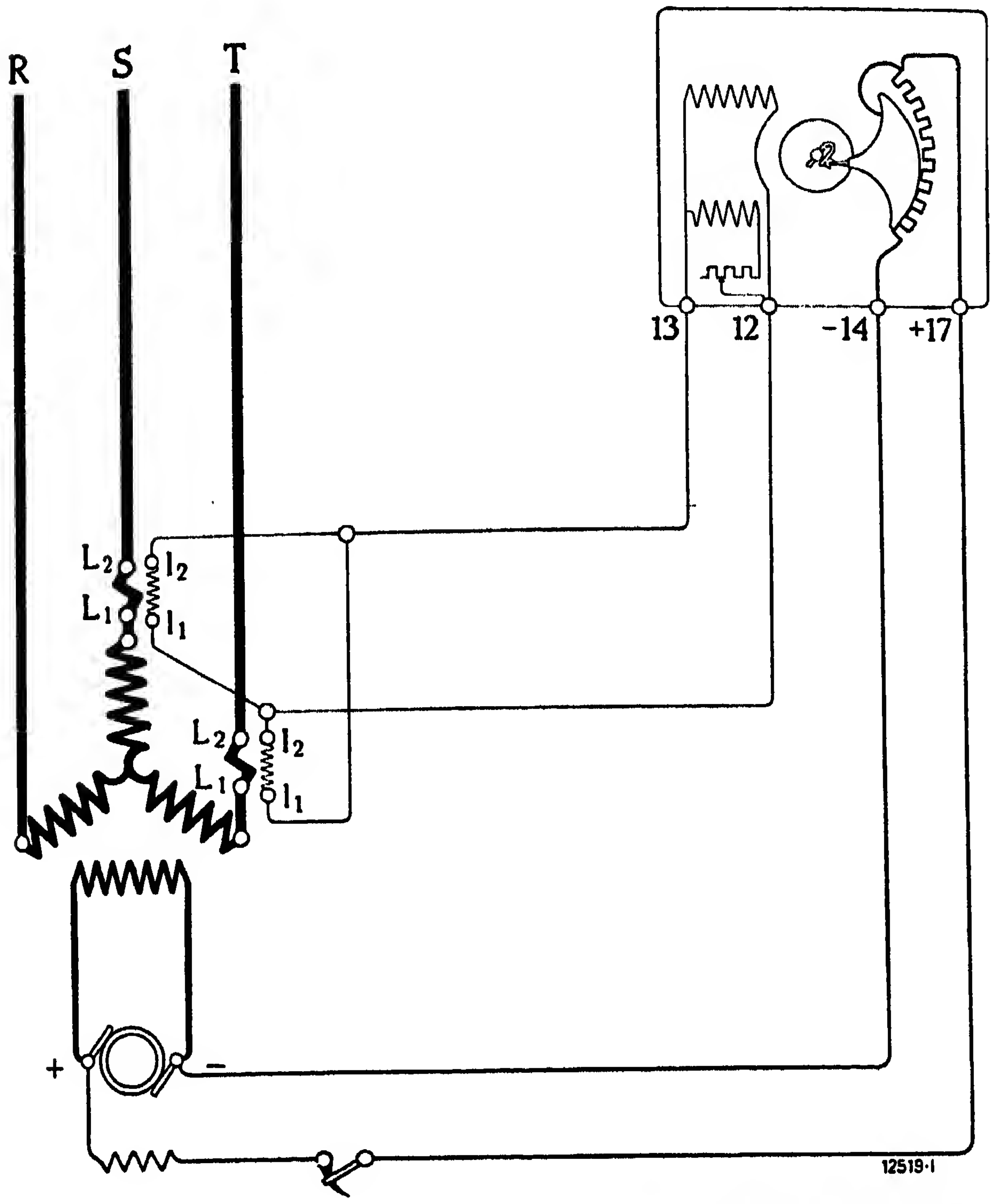


Fig. 2. — Diagram of connections of a three-phase alternator with current-limiting regulator.

short-circuited when the rotor is on 0, and this is the position it takes up under normal running conditions.

Should the alternator current now rise above that for which the current-limiting regulator is set, the movable sectors roll along the contacts in a clockwise direction, and gradually put more and more resistance into the field of the alternator exciter. When the movement is arrested by the stop in position 4, all the resistance is in, and the excitation consequently has its lowest value.

As soon as the fault which caused the abnormal rise of current has been removed, the sectors of the regulator return automatically to the zero position with the result that the resistance is cut out and the normal working conditions are restored.

The value of the current necessary to give an electro-magnetic torque just sufficient to balance the action of the spring in position 4 is about 15 % higher than that which gives a balance in position 0. The current-limiting regulator has therefore a so-called "static" characteristic, the static difference amounting to about 15 %. By means of the adjusting contact in the lower part of the regulator, it is possible to set it to operate with any desired current value between 100 and 200 % of the normal full-load current of the alternator.

THE USE OF THE AUTOMATIC CURRENT-LIMITING REGULATOR IN CENTRAL POWER STATIONS.

First example:— The diagram of connections of a power station with three outgoing lines is given in Fig. 5. The load consists in each case of lamps and induction motors and line 3 has, in addition, a synchronous motor connected near the point of consumption for the purpose of improving the power factor and reducing the pressure drop and losses in the line.

Suppose a short circuit takes place at X on line 2, then, with the usual type of overload tripping device hitherto employed, set to operate after a very short interval, it is probable that all three feeder circuit breakers will open — breaker 2 on account of the short-circuit current, and breakers 1 and 3 on account of the fact that the motors connected to them take larger currents owing to the fall in pressure.

When the alternators are fitted with current-limiting regulators, the sequence of events will be as follows:—

Immediately the current rises on account of the short circuit, the regulators reduce the excitation of the alternators, and consequently the pressure is diminished. Should the fault be of a temporary nature, this diminution will probably extinguish the arc, in which case the current-limiting regulator, operating in conjunction with the pressure regulator, immediately begins to re-establish gradually the normal running conditions. It is at this stage that the regulator shows itself infinitely superior in its action to any other type. The superiority will be evident when considering the case of a more serious fault which will not clear itself. Obviously here the short circuit must be isolated and the tripping of the switch directly controlling

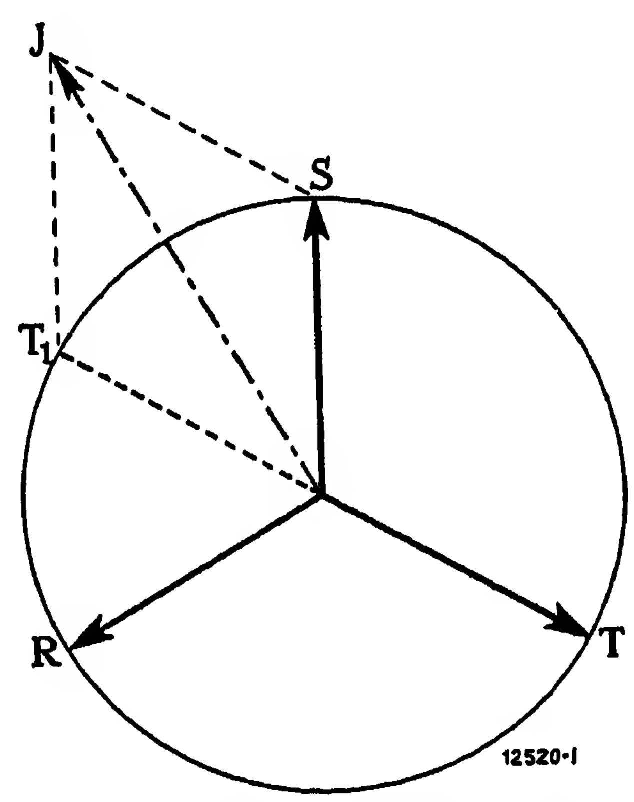


Fig. 3. — Vector diagram showing the resultant current with the current-limiting regulator connected to two phases.

the short circuited section is necessary, but it will be noted that there are many refinements about the action of the regulator in these circumstances which are in themselves a great aid to the protection of the

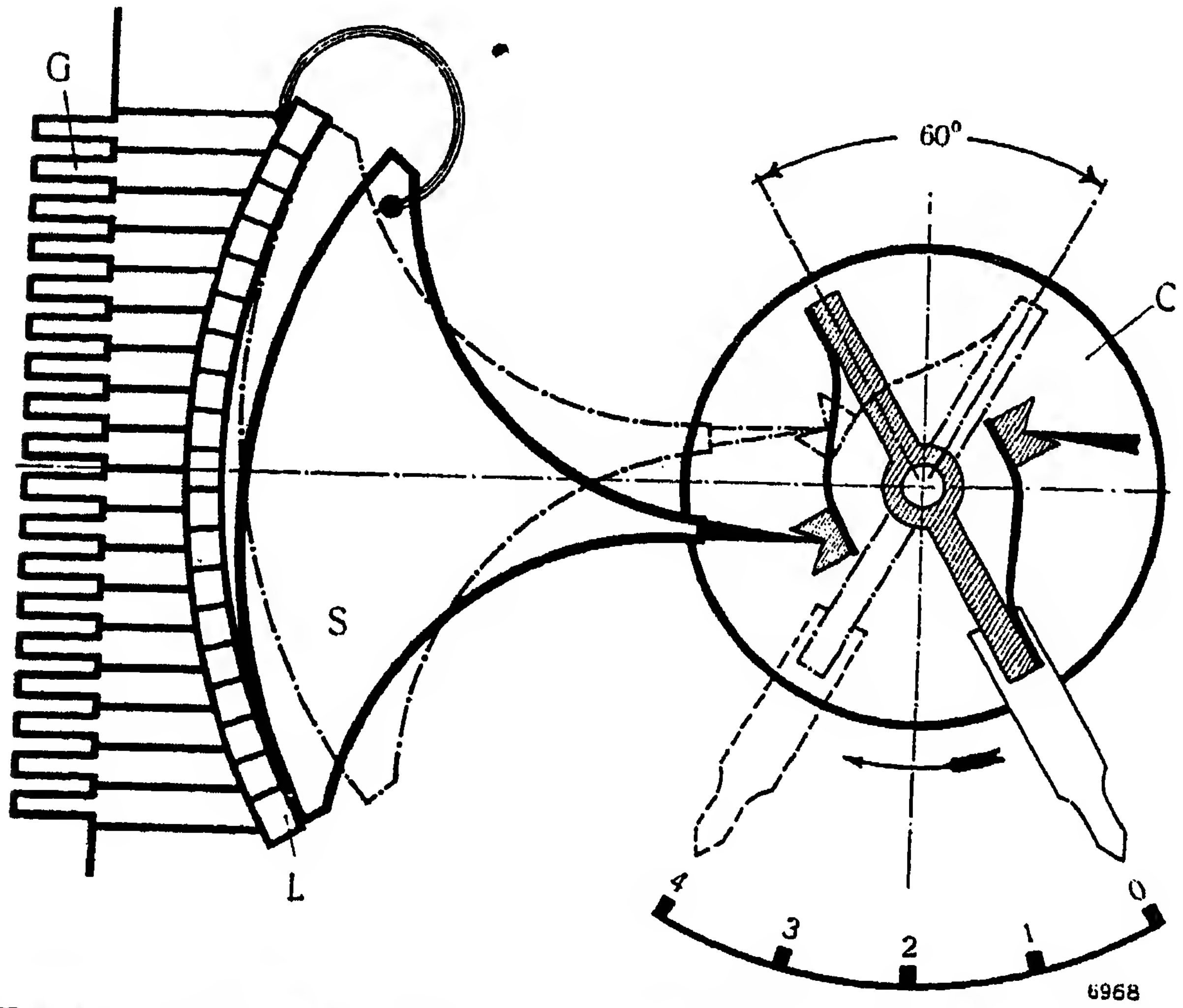


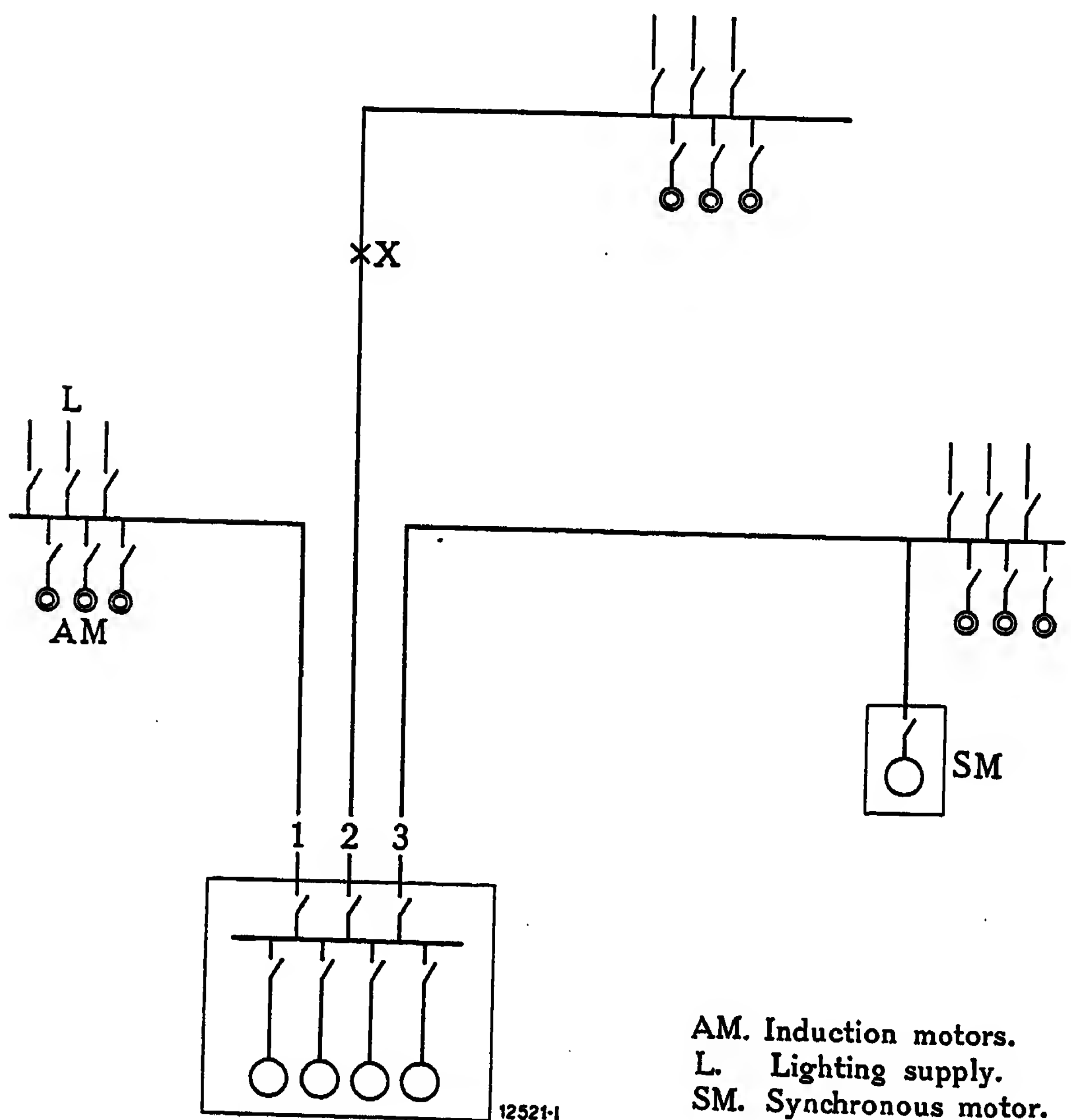
Fig. 4. — Rotor, sector, and contact segment of a current-limiting regulator.

system. The instantaneous reduction of the pressure and of the current by the current-limiting regulator minimises the destructive effect of the short circuit, while machine cables and switchgear can now carry the reduced short-circuit current for a reasonable time and allow the circuit breaker relays to be set with considerable time lag. This increases to a great extent the possibility of selective tripping, i. e., of tripping only that switch which is necessary to isolate the short circuit.

Owing to the increased current resulting from the fall in pressure, the induction motors will also be disconnected from the mains; this occurs before the breakers 1 and 3 can operate, as the time lag of the motor switches is shorter. Since the abnormal current in lines 1 and 3 is reduced as soon as the induction motors are disconnected, the corresponding main circuit breakers will not trip at all, so that there is no interruption in the supply of the synchronous motor and the lamps. Should it happen that the time, for which the relay of circuit breaker 2 is set, has elapsed without the arc having ceased, the tripping gear will operate, and cut off the supply to the faulty line. It should be noted that this breaker opens under very favourable circumstances, as the short-circuit current has been reduced by the action of the current-limiting regulator. Dangerous over-potentials at switching off are therefore not liable to occur. An idea of the extent to which the breaker is relieved when a given resistance is in the circuit containing the fault, may be obtained by considering that the load to be interrupted varies as the square of the current. Under certain circumstances, on a system where several power stations work in parallel, it will be possible to employ a smaller, and consequently cheaper type of oil circuit breaker than would be possible if no current-limiting regulators were installed.

By the additional provision of a current-limiting regulator for the synchronous motor, this machine, upon the occurrence of a short circuit, is prevented from working as an alternator with an excessive current. Not only is the synchronous motor thus protected against overload, but the breaking effect due to the short-circuit current is considerably reduced. Consequently, the speed will scarcely fall during the short time that elapses before the action of the regulators causes normal conditions to be resumed. The result is that as its speed has not varied much from synchronism, the motor will be pulled into step far more easily when the pressure comes up again, than would otherwise have been the case.

Often greater damage and disorder are caused during the resumption of the normal running conditions than during the actual short circuit itself. General experience is that when a great number of alternators and power stations are running in parallel, a far greater number of switches are tripped after the short circuit



AM. Induction motors.
L. Lighting supply.
SM. Synchronous motor.
X. Short circuit.

Fig. 5. — Diagrammatic arrangement of a central station with three separate supply feeders.

has been cleared and when the machines are trying to pick up synchronism again, than during the actual short-circuit period. The reason for this is the excessive exchange currents which take place between the different machines after the pressure has been suddenly

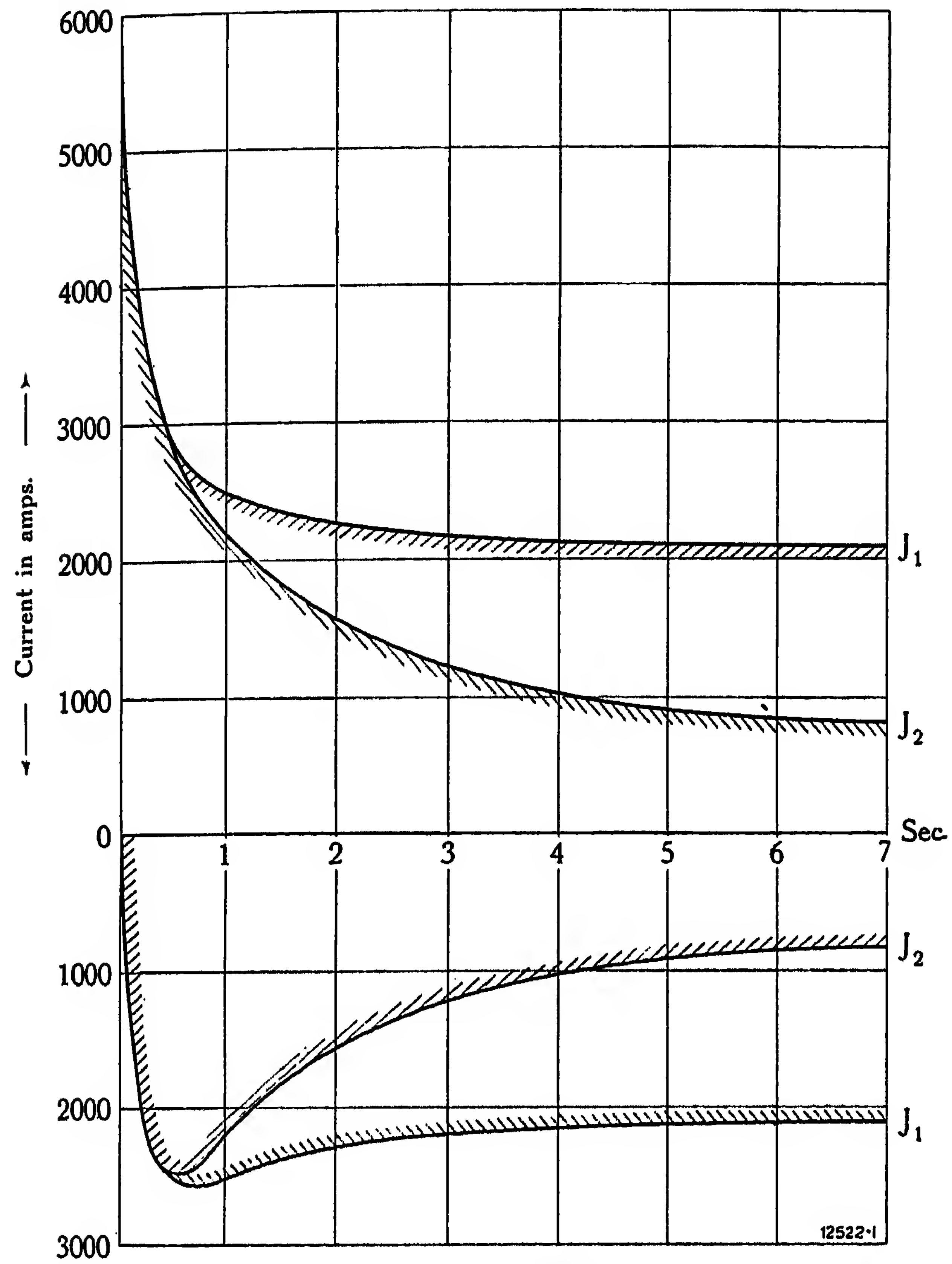


Fig. 6. — Current in amperes. Curves showing how the short-circuit current falls off under the influence of the current-limiting regulator.[1]

Peak values of the current with a short circuit on all three phases of a 4600-kVA alternator (unsymmetrical short circuit).
J_1. Current without regulator.
J_2. Current with regulator.

restored, on the short circuit being cleared. The generating units have all been braked down to the same extent, the braking effect depending on the characteristic of the prime movers as much as on that of the alternators. The alternator phases are at different angular positions, and the exchange currents will be proportional not only to the angular difference but also to the re-established pressure. If the excitation instead of being diminished during the short circuit, has, on the contrary, been increased by the action of the pressure regulator trying to keep up normal pressure, the re-established voltage may be far above the normal value, and the exchange currents will then certainly trip the switches and dislocate the service. Similarly, the speed of asynchronous motors in service at the time will fall during the short-circuit period, and their excessive demand for current, when the re-established pressure rises quickly to a high value, will cause the circuit breakers of these motors to be tripped.

This interruption of the service is prevented by the current-limiting regulator which, having reduced the excitation to a great extent during the sustained short circuit, allows only a gradual rise of the pressure until it reaches its normal value. Should excessive exchange currents have a tendency to rise between the machines, the current-limiting regulator will keep down the excitation and re-establish it only gradually so as to allow the machines to be pulled into synchronism slowly and without causing such excessive exchange currents as would trip the switch and interrupt the parallel operation of the machines.

Second example: — Fig.7 represents two power stations A and B working in parallel. Station A was originally intended for the power and lighting supply of a town. In the course of time the demand grew to such an extent that it exceeded the capacity of the plant, and additional energy had to be obtained from station B. If a short circuit now occurs at X in the interconnecting line, and the breakers are simply provided with overload releases in the usual way, the supply will be greatly disturbed, as the capacity of station A is not nearly large enough to provide all the energy needed in the town. The alternators will be excessively overloaded, and their breakers will open, with the result that

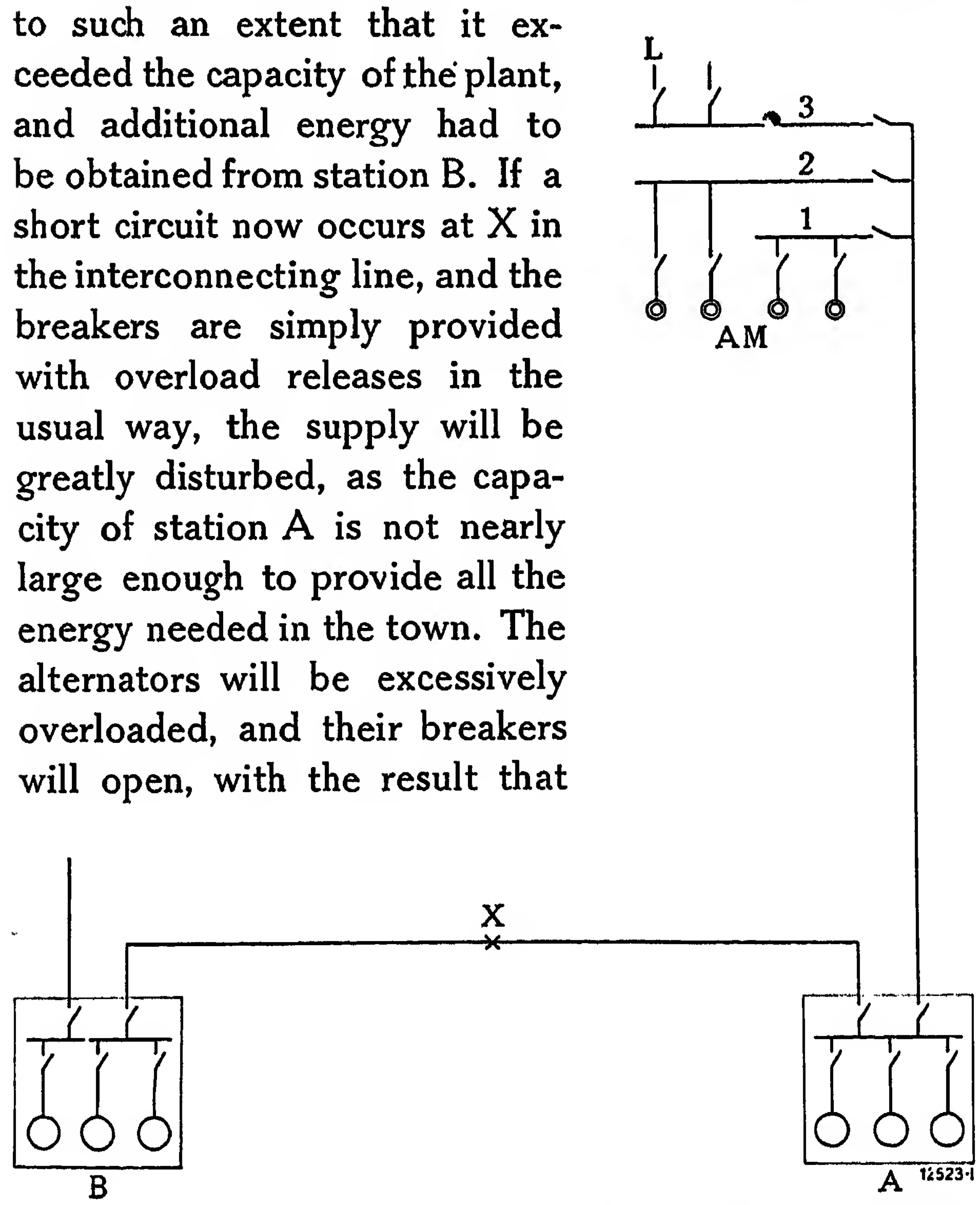


Fig. 7. — Short circuit on the interconnecting feeder between two stations operating in parallel.

AM. Induction motors. X. Short circuit.
L. Lighting supply. A, B. Power stations.

[1] Curves of the short-circuit current usually indicate the r. m. s. value, but in the above figure the peak values have been plotted. By taking account of both the positive and negative peaks the unsymmetrical distribution of the short-circuit current wave is very clearly shown.

not only is the supply cut off, but the alternators no longer remain in parallel with one another. It is possible to guard against the latter occurrence to a certain extent, by providing an additional circuit breaker through which

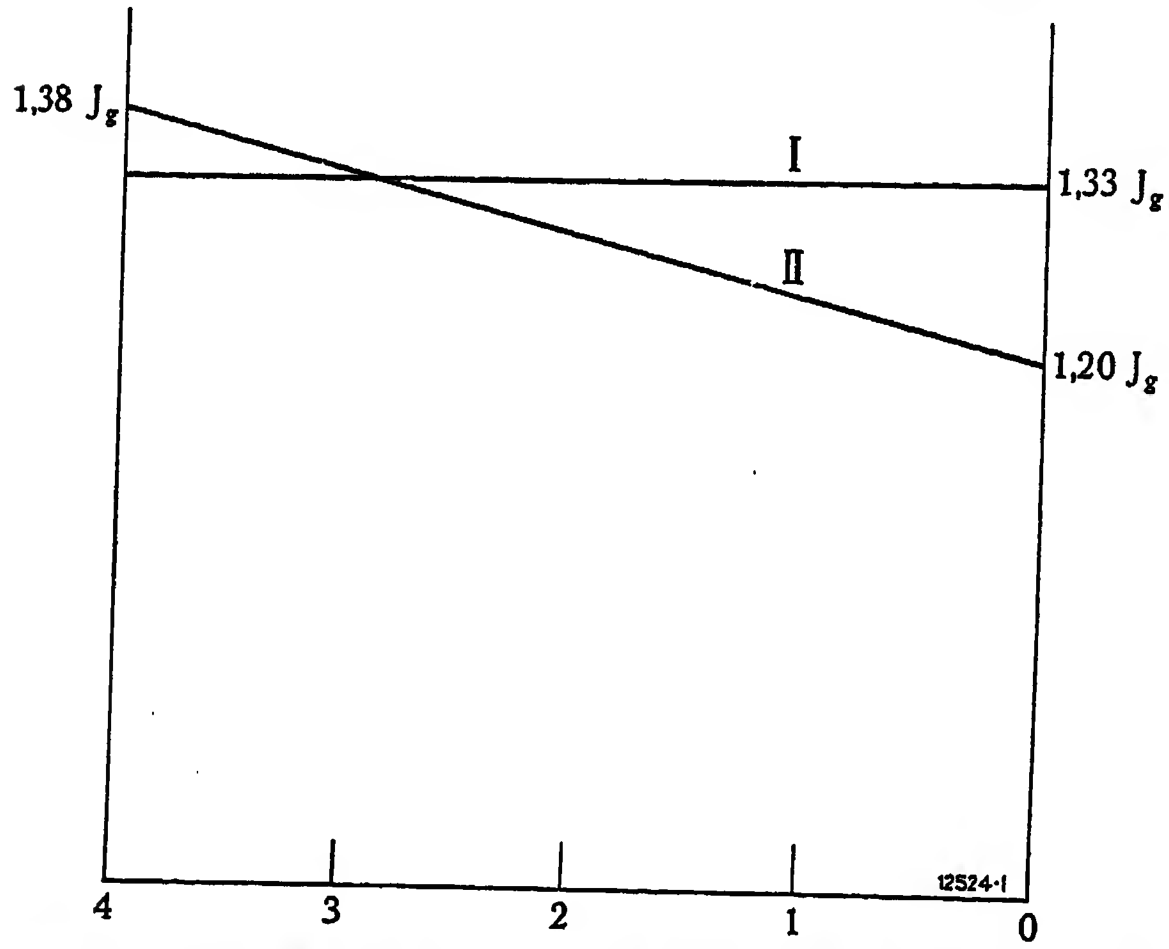


Fig. 8. — Graphical illustration of the way the operation of the overload relay depends on the static characteristic of the current-limiting regulator.
Nominal full-load current of the generator = $1 \times J_g$.

the whole power of the plant A is transmitted, and connecting the feeder to the outgoing side of it, instead of to the alternator bus-bars. With this arrangement if the alternator breakers are not set for very close tripping, the majority of these machines, if not all of them, will remain in synchronism. However, the disadvantage that the town supply will be interrupted is not overcome.

The case is quite different when the alternators have current-limiting regulators. Supposing again that a temporary short circuit occurs, and that regulators of this description are provided for the machines in both power stations, then the interconnecting feeder will not be cut out, and regular synchronous running conditions will be re-established automatically after the fault disappears. If the latter is so serious that it is impossible to avoid the disconnection of the feeder from the stations, then the current-limiting regulators will, nevertheless, prevent the alternators in station A from being overloaded, since they bring the pressure down so much that the maximum allowable current is not exceeded. The supply to the town is consequently maintained, though at a somewhat reduced pressure. If the total demand on the town mains is much greater than the aggregate output of the alternators in power station A, the reduction of pressure will be considerable, owing to the influence of the current-limiting regulators. The motors connected to feeders 1 and 2 will then probably take such an increased current that the breakers on these lines will open. It may happen, however, that the drop in pressure is so great that the supply to the motors is first interrupted automatically at their switch boxes, so that the circuit breakers 1 and 2 remain closed. In either case, the load on the plant in station A will be reduced, with the result that the pressure will rise again. Whether it comes right up to normal or not, depends on the total load remaining on the mains. If this is more than the alternators can carry, it will be necessary for the attendants in station A to switch out the less important feeders until the alternators are so far relieved that their pressure can come up to normal. By suitably setting the time lags of the various feeder circuit breakers, it is possible to make them trip in the manner required without any necessity for manual operation, thus ensuring that the supply to the more important parts of the system (the lighting feeder 3, for instance) is maintained under all circumstances.

This example also shows that the current-limiting regulator is not only a reliable apparatus for preventing the plant being excessively loaded, but also an extremely valuable device for maintaining the supply when disturbances occur.

OVERLOAD TRIPPING GEAR FOR THE ALTERNATOR CIRCUIT BREAKER.

It has been shown above, that the current-limiting regulator completely protects the alternators from being excessively overloaded by the sustained short-circuit current, and that there is no need to disconnect these machines from the mains in order to safeguard them from injury. There are, however, circumstances in which it may be advantageous to have the alternator circuit breaker arranged to trip on overload. This is the case, for instance, when the fault is in the station itself. The current-limiting regulator protects the generating plant from dangerous overloads, but all the alternators will send current into the short circuit until the attendant switches them off by hand, if the breaker is not set to do it. Although the pressure of the alternators is reduced by the regulator, the total short-circuit current can still be very large, and can do appreciable damage in the immediate vicinity of the fault, if it flows for any length of time.

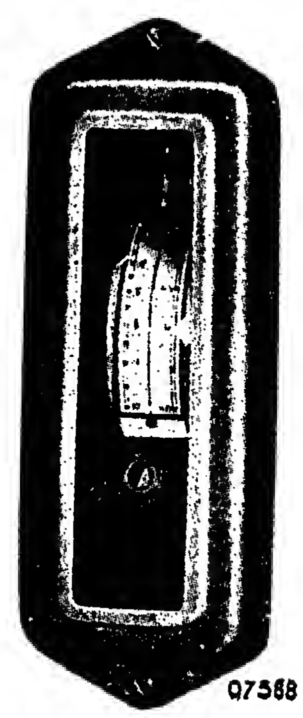


Fig. 9. — Overload time-limit relay, Type H 2/1.

It is evident, therefore, that in the case when the regulation of excitation is insufficient to reduce the current, the alternators must be automatically switched off. Nevertheless, the machines must be disconnected only if it is no longer possible to keep them running

in parallel. Otherwise there would result the same dislocation of the supply as takes place with ordinary overload protection. The desired result is obtained by employing a single-pole relay connected in series with the motive system of the current - limiting regulator and fed from the same current transformer. Fig. 8 shows graphically how the static characteristic of the current-limiting regulator is utilised to make the operation of the overload time-limit relay depend on the short-circuit current in such a way that the relay will cut off the alternator only if absolutely necessary. The inclined line represents the static operating characteristic of the current-limiting regulator. The lower end of this line corresponds to position 0 of the apparatus in which, say, 1·2 times the normal full-load current would flow; thus the current-limiting regulator is so adjusted that the torque exerted by the motive system when 1·2 times the normal current flows just balances the torque of the spring in position 0. Since the regulator has 15% static difference, it follows that $(1{\cdot}2 \times 1{\cdot}15) =$ 1·38 times the normal current would be necessary to give a balance in position 4. Suppose now that the overload relay — which has no static characteristic — is set for 1·33 times the normal current; then the horizontal line representing this value will cut the inclined characteristic of the current-limiting regulator at a point corresponding roughly to position 3 of the latter.

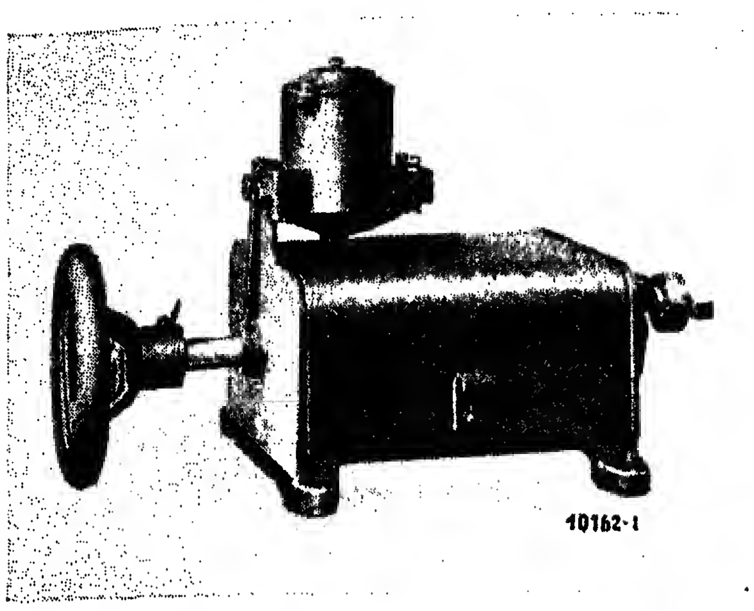


Fig. 10. — Change-over exciter switch with solenoid release.

The consequence of this will be as follows:—

In order to reduce the excitation as quickly as possible when a sudden overload occurs on the generating plant due to an auxiliary station being disconnected or to a short circuit, the current-limiting regulator will rotate right to position 4. It will not remain at the end of its travel, but will return gradually till it takes up a position of equilibrium corresponding to the amount of resistance that has to be left in the exciter circuit in order to reduce the alternator pressure to a value such that a balance is again obtained in the regulator. If it is only a question of the alternators being overloaded, or of a short circuit at a point remote from the power station, the steady position that the regulator takes up will lie between 3 and 0. The overloaded relay of the circuit breaker consequently remains inoperative, no matter how long the fault persists. In the case of a very heavy short circuit, the feeder breakers, which are set with a relatively small time lag, will

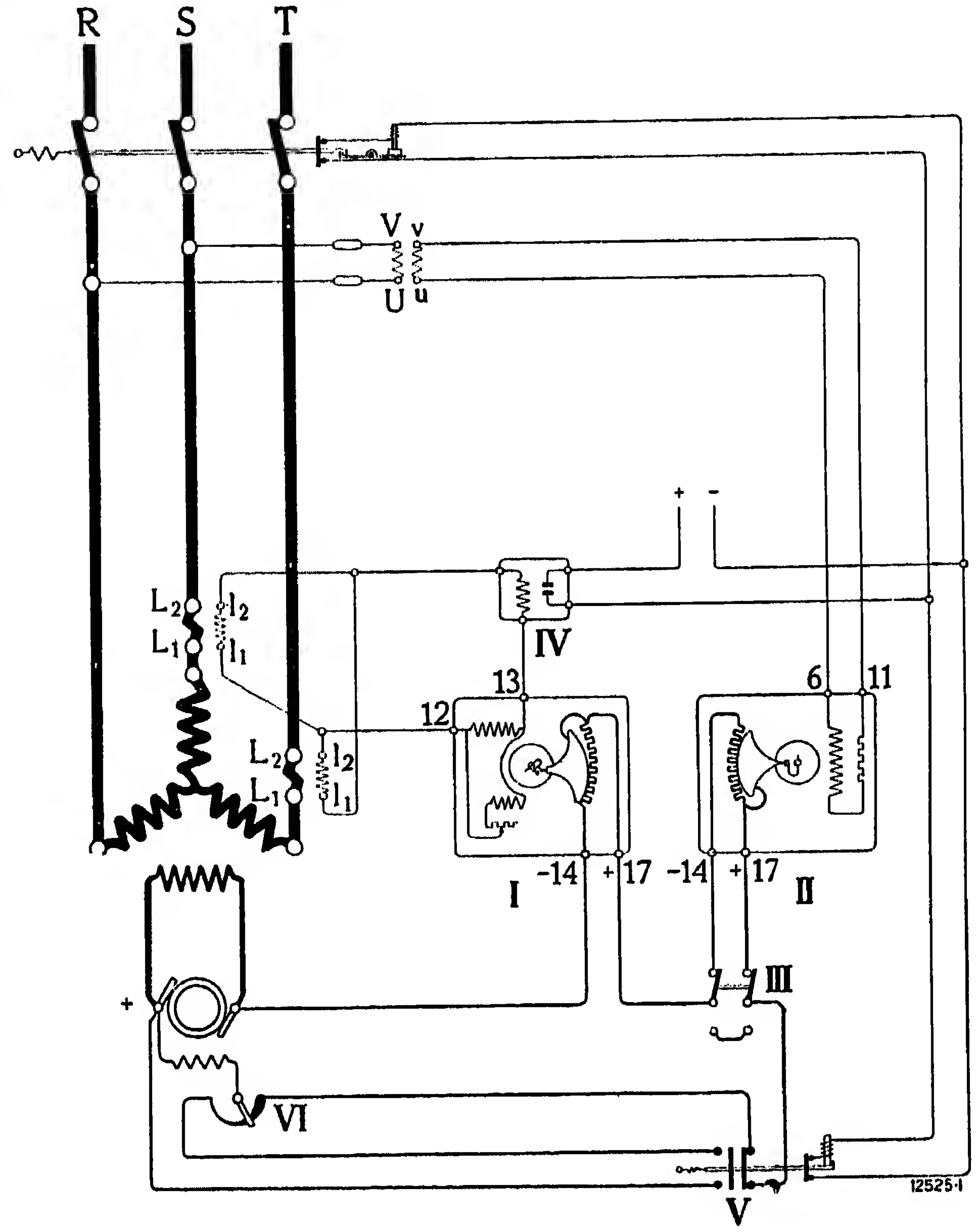


Fig. 11. — Diagram of connections of a three-phase alternator with current-limiting regulator I, automatic pressure regulator II, overload time-limit relay IV, and change-over exciter switch V.

open and relieve the machines. Hence the overload relays of the main breakers do not operate, and the alternators will continue to run in parallel.

When the fault is inside the station, the current-limiting regulator has to insert the whole resistance to cause the necessary reduction in the alternator current, and it therefore takes up a steady position at 4, or very near there. As the corresponding alternator current is approximately 1·38 times the full-load current, the overload relays will come into action and cut out the alternators at the end of the period for which the time lag is set.

It is possible that a fault may develop between the alternator and the circuit breaker or in the breaker itself. Should this occur, a field change-over switch (Fig. 10) can be used, its action being simultaneous with that of the opening breaker. The solenoid of this change-over switch is in parallel with the tripping coil of the main circuit breaker, so that both are energised together when the time-limit relay operates. The diagram of connections of an alternator with automatic pressure regulator, current-limiting regulator, overload relay, and field change-over switch is given in Fig. 11.

ADVANTAGES OF THE BROWN BOVERI AUTOMATIC CURRENT-LIMITING REGULATOR.

It has been shown in the preceding pages that the current-limiting regulator is a protective apparatus that enables the supply to be maintained in spite of disturbances, and this most important feature has been brought out by considering certain practical cases. Nevertheless, the many advantages offered by the current-limiting regulator are worth enumerating. To avoid excessive detail, however, it will suffice if only those points are referred to where it affords protection, which would be either inadequate or entirely lacking if the ordinary overload-relays were used.

1. Alternators are completely protected from the injurious effects of a sustained short-circuit current without being disconnected.

2. Stresses and destructive effects resulting from the short-circuit current are limited by reducing the excitation.

3. Extinction of the short-circuit arc is greatly assisted by the reduction of the pressure.

4. Reliable selective operation of the circuit breakers in series, and having different time settings, is ensured by the increased time lag which can now be used without endangering the plant.

5. The duty of the circuit breakers is lightened by the reduction of the pressure and current.

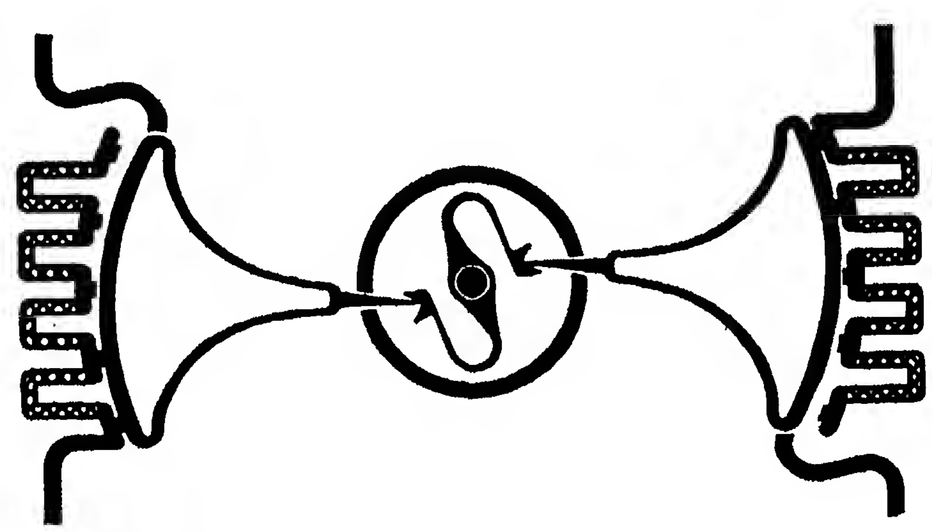
6. The falling out of step of the alternators is avoided, and normal running conditions are re-established automatically after the fault is cut out.

7. Absolute reliability is ensured without reliance having to be placed on the attendants. The current-limiting regulator is, therefore, an absolute necessity in automatic stations, and in others is, in time of emergency, a great help to operators who are left free to take readings and observe how the plant operates.

H. Kloninger.

BROWN BOVERI
QUICK-ACTING REGULATORS

THE AUTOMATIC PRESSURE REGULATION OF ALTERNATORS



BROWN, BOVERI & CO.

BADEN (SWITZERLAND)

786E

April, 1923

CONTENTS:

BROWN BOVERI QUICK-ACTING REGULATORS.

THE AUTOMATIC PRESSURE REGULATION OF ALTERNATORS.

Decimal index 621. 314. 5.

1. INTRODUCTION.

The automatic pressure regulation of alternators is so extensively practiced to-day, that it seems unnecessary to give it special recommendation. Nevertheless, it is, perhaps, not superfluous to recall that the invention of the automatic pressure regulator resulted in fundamental changes in alternator design. The demand, which was maintained for many years, for the smallest possible inherent pressure variation, could finally be dropped and the heavy, expensive types of alternator built to meet this condition disappeared. They were replaced by units of lighter design which are cheaper, more economical in operation, and can be made practically short-circuit proof.

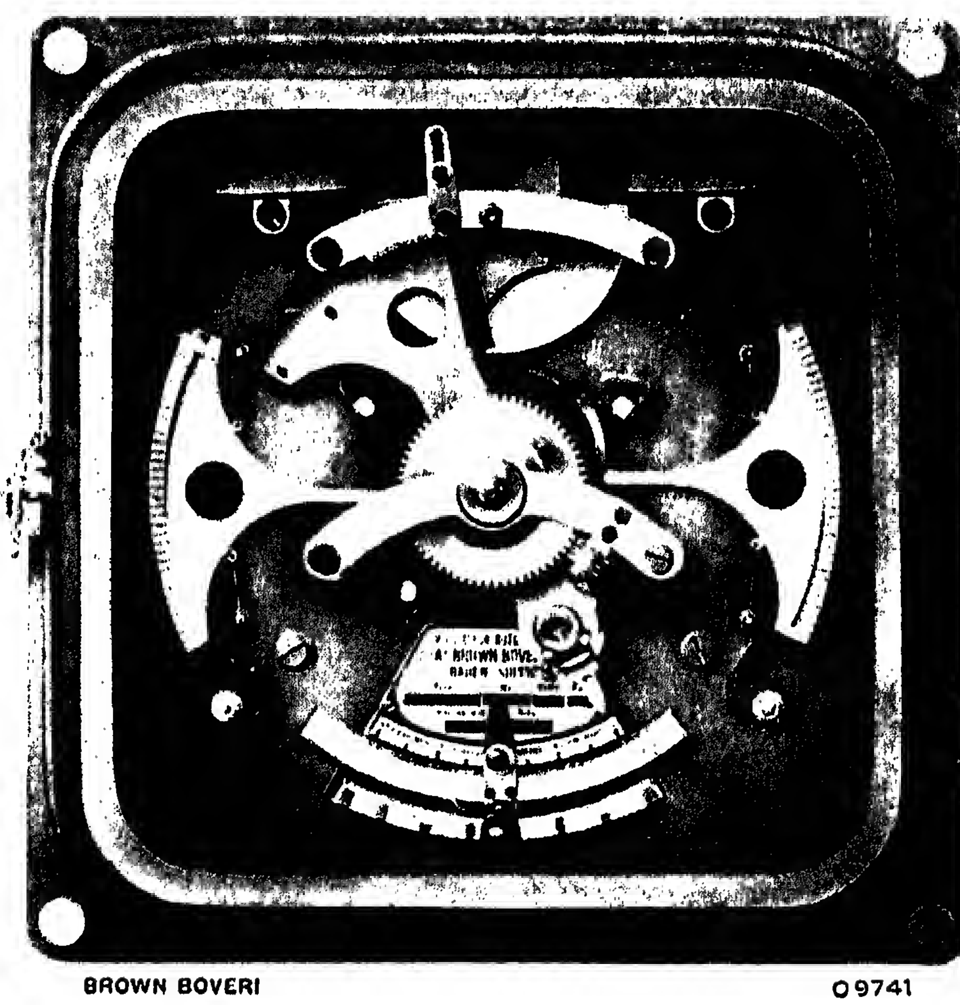


Fig. 1. — Regulator, Type A 2/1, small model.

However, in order to prevent the considerable inherent pressure variations of these new alternators from influencing the terminal voltage undesirably, the use of a perfectly reliable *"quick-acting" regulator* is absolutely essential.

The duty of this regulator is to compensate effectively the results of load fluctuations by immediately modifying the excitation of the alternator.

A *quick-acting regulator* differs from an ordinary automatic regulator, not only in the rapid movements of the regulating mechanism, but, to a far greater extent, in its characteristic method of regulation.

It is well known that every alternator with its exciter has a certain electro-magnetic inertia which is termed the *time constant*. The magnitude of this constant depends upon the coefficients of self-induction and on the ohmic resistances of the field circuits of alternator and exciter. In practice, for a complete set, this constant has a value between 2 and 16 seconds, or even more. In other words, when the excitation of the alternator varies by a given amount, a certain time, from 2 to 16 seconds, elapses before the pressure reaches the value which corresponds to the new excitation.

The time required for the movement of the regulating mechanism of an efficient quick-acting regulator varies between $^1/_{10}$ and $^1/_2$ second; consequently, it has a relatively slight influence on the total time required for the regulation to take effect, as the time constant of the set is by far the more important factor. The retarding influence of the time constant can be neutralised to a great extent by making the quick-acting regulator *over-regulate*, immediately after a fluctuation in the load, and then return gradually to the exact excitation current which really corresponds to the new load conditions.

In order to prevent the over regulation and subsequent return movement from causing continual hunting, an elastic recall device is provided which breaks off the over-regulation at the right moment and starts the return movement. *The powerful over-regulating effect and the elastic recall are*

distinguishing features of the quick-acting regulator; the design of the regulating mechanism itself is a less important factor in rapid regulation. Practice has shown that vibrating contacts and suitable rolling contacts give equally good results if over-regulation and recall device are mutually well balanced.

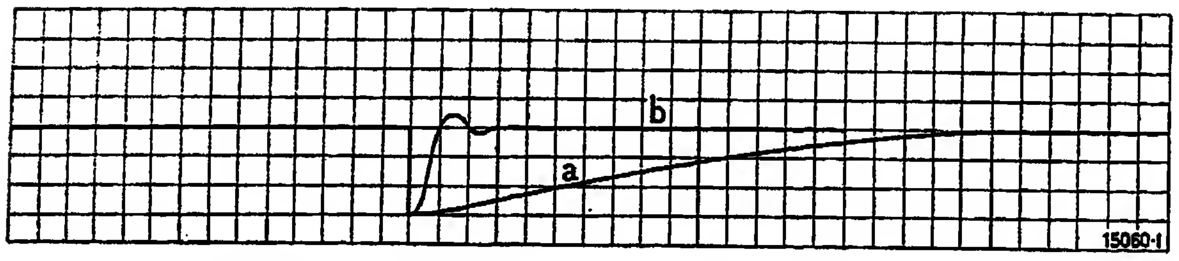


Fig. 2. — Regulation curve showing the variation of the alternator pressure:

a. When an automatic regulator without over-regulation is used.

b. When a quick-acting regulator with strong over-regulation and elastic recall device is used.

Abcissæ: Time. Ordinates: Pressure.

The controversy as to whether *central regulation* of the whole power plant or *individual regulation* of each separate unit is more desirable, no longer exists. As long as automatic pressure regulators were unknown, it was considered advantageous to link up the field rheostats of the individual alternators to a common control, so that the operator on duty might regulate the working pressure by means of a single handwheel. The first automatic regulators produced were built, so to speak, to replace this operator, and control all the field rheostats, either purely mechanically by means of a control motor, or electrically by vibrating contacts which short-circuited the field rheostats periodically.

In many cases however, it is impossible to combine the whole station control in this way, and it is then necessary to divide the plant into several independent busbar systems, installing a separate automatic regulator for each. Further, the alternators must be controlable by the regulators in whatever manner it may be desirable to connect them, and it is impossible to realise this condition without very complicated wiring arrangements.

As opposed to central regulation, *individual regulation* may be adopted, each set being equipped with its own quick-acting regulator. In this case the station can be subdivided so as to form as many separate systems as desired. The generator sets, each of which, to-day, is always provided with its own built-on exciter, form quite independent units and any fault in the station will affect and put out of operation only the unit involved.

In power stations where the generators are of different designs or are driven by dissimilar prime movers, individual regulation has the further advantage that the quick-acting regulator can be set to suit exactly the characteristics of the machine to which it belongs. Thus, the best results are attained with regard not only to regulation but also to the most economical use of each individual set.

When the power-station load is suddenly thrown off, or if the oil switch of any alternator opens automatically, the individual regulators prevent the subjection of the machines or the switchgear to excessive stresses, because the pressure of each alternator is maintained constant even after parallel operation has ceased. Under these conditions, if central regulation be used the alternator pressure increases considerably, especially if the regulator be of the vibrating-contact type. If a fault such as a short-circuit occurs, causing the busbar pressure to drop, this type of regulator has the undesirable property of giving very strong excitation, which may even reach a dangerous value.

Absolute reliability of operation is, to-day, justly demanded of a quick-acting regulator. It cannot be denied that regulators with vibrating contacts only meet this condition when the contacts are carefully cleaned at regular intervals and kept in good order. In order that reliability may be secured independent of supervision, the contacts of a quick-acting regulator ought not be subject to wear.

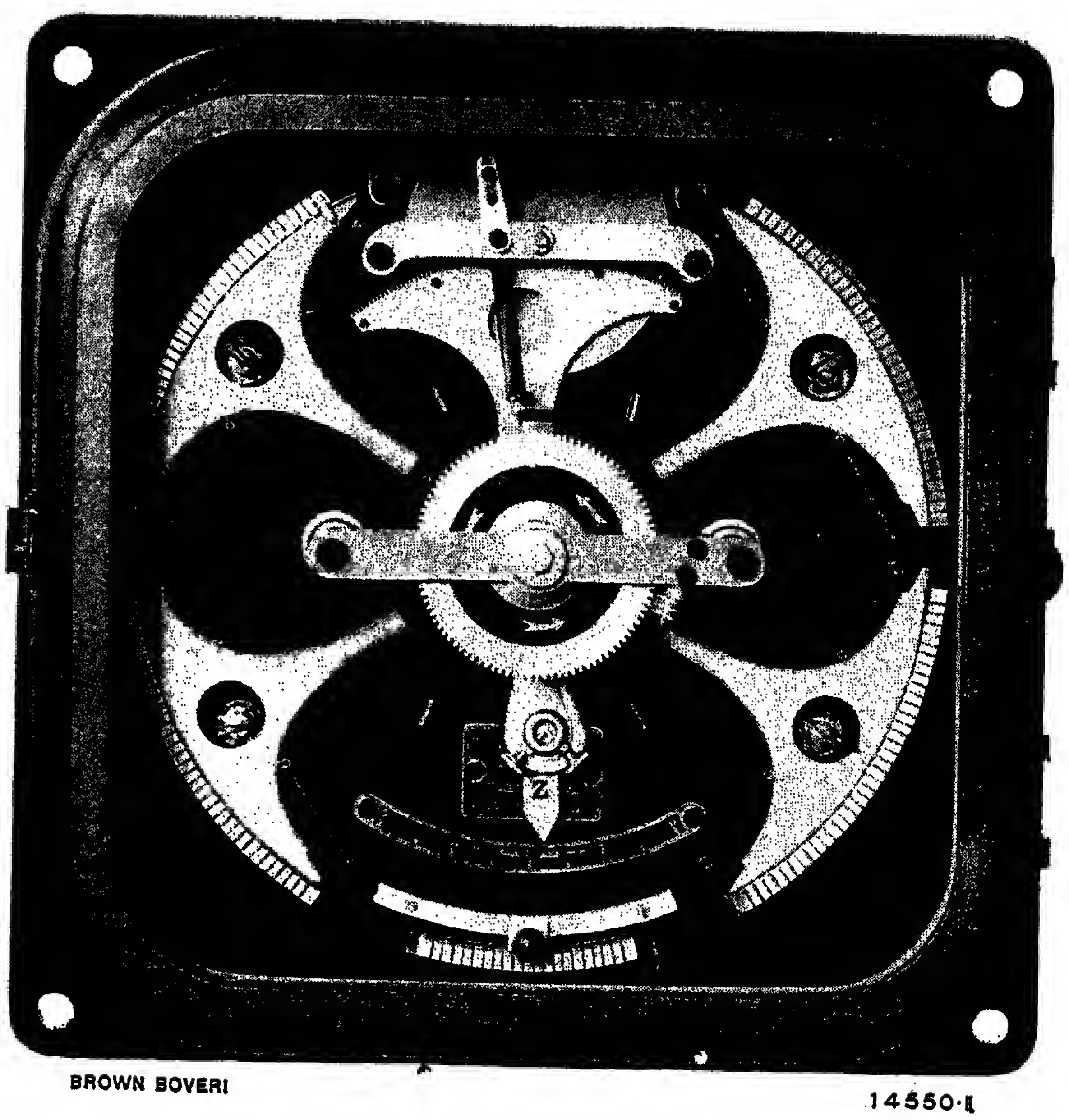


Fig. 3. — Regulator, Type A 4/1, large model.

These conditions are fulfilled by the *Brown Boveri quick-acting regulator* alone. It is the only existing apparatus which meets fully all the requirements mentioned.

The strong *over-regulation* combined with the *elastic recall* is a guarantee of rapid regulation. *The rolling-contact system excludes all wear* and does away with the necessity for supervision.

The *simplicity* of the regulating mechanism and the *adaptability* of the apparatus to any type of alternator or exciter are a guarantee of sure, stable regulation of each unit.

As opposed to the regulator with vibrating contacts which, under normal conditions, uses effectively only a part of the total excitation range, *the Brown Boveri regulator makes use of the whole range for actual regulation;* thus, relatively small exciters can be used, and, if a fault occurs, the resulting over-excitation is always moderate.

The general popularity of the Brown Boveri regulator and the wide-spread use of the apparatus since its appearance on the market are obvious proofs of its practical utility and quality.

2. DESIGN AND OPERATION OF THE BROWN BOVERI QUICK-ACTING REGULATOR.

As is well known, the pressure regulation of alternators is carried out by means of resistances, which are usually inserted in the circuit of the exciter field.

The single wire helices g (Fig. 4), which constitute these resistances, are connected to heavily silver-

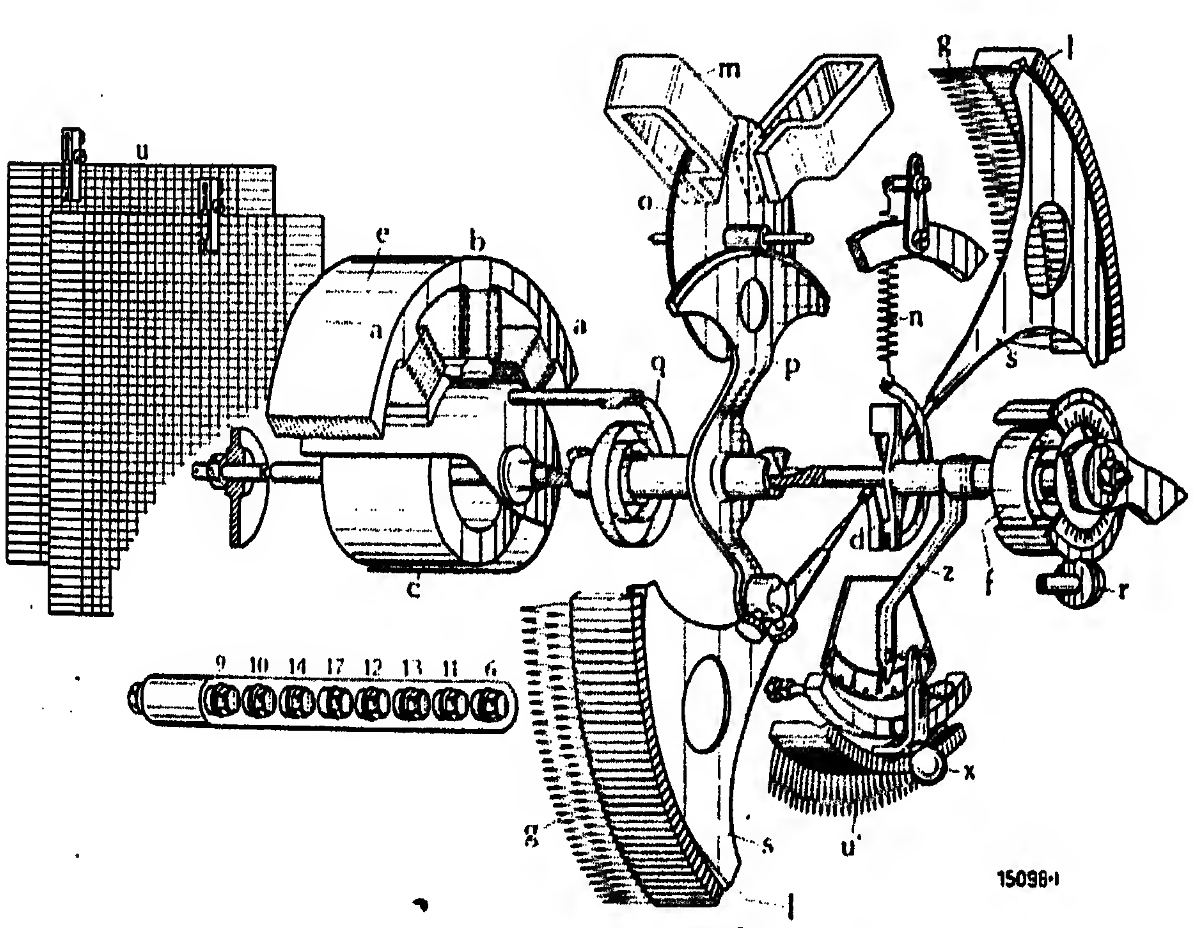


Fig. 4. — Motive system and regulating mechanism of quick-acting regulator, Type A 2/1.

plated contacts l which are arranged round arcs of a circle about the centre of the apparatus. According to the type of quick-acting regulator, two or four such sets of contacts are used. Their interior surface is grooved out to form a track in which the contact sectors s roll. The needle point of each sector is cradled in a jewelled cup and is carried through a small arc of a circle when the regulating mechanism moves. The springs on which the jewelled cups are mounted are sufficiently strong to give good contact pressure between the sectors and the contacts. The counter pressure exercised on the centre is taken up by a second sector placed symmetrically with the first. In this way the movement is practically frictionless and the contact pressure is adequate and uniform.

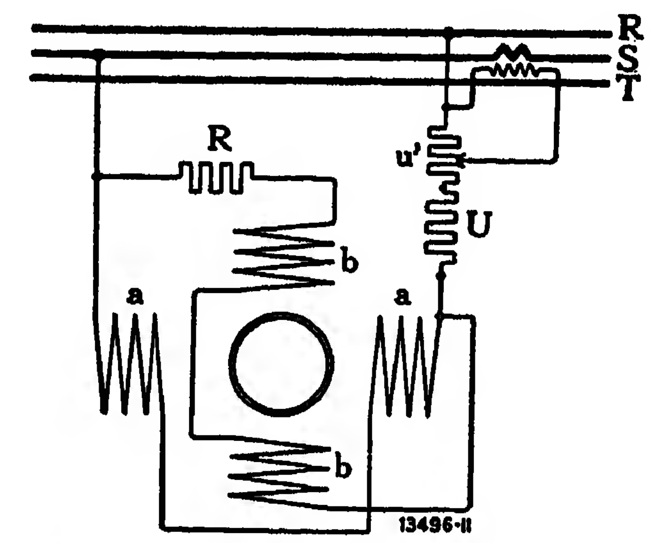


Fig. 5. — Diagram of connections of the motive system of the quick-acting regulator for three-phase current.

As a result of this advantageous arrangement, a very slight torque is sufficient to cause rotation of the contact sectors and, therefore, to change the excitation. This torque is produced by a device based on the well-known Ferraris principle which is very generally used in precision instruments. The main coil a and the auxiliary coil b are connected through terminals 6 and 11 across a composed phase of the alternating-current system (see Fig. 5). By means of appropriate resistances U and R, an auxiliary phase is created and with it a rotating field. The torque exerted on the aluminium drum c by this rotating field is transmitted to the spindle. The latter has steel-tipped ends carried between jewels.

The inner extremity of the main spring f is fastened to the front part of the spindle, the outer extremity being secured in a cylindrical housing which is supported by the main bridge. The auxiliary spring, which influences the spindle through the agency of a bow-shaped lever, is intended to supplement the effect of the main spring in such a way that, whatever position the drum may occupy, a constant torque is exerted on the motive system. As a certain electromagnetic torque corresponds to each value of the alternating pressure, it is possible so to set the main spring f that the two torques counterbalance each

other exactly and the motive system is in equilibrium at the pressure concerned.

Owing to the action of the auxiliary spring this setting can be so made that there is equilibrium at any position of the motive system. A regulator of this kind with neutral equilibrium is called an *astatic regulator*. The astatic pressure regulator tends therefore to maintain the alternating pressure constant for any position of the regulating mechanism. As a result of the very slight friction and the condition of neutral equilibrium of the motive system, quite small torques can produce considerable displacements of the contact sectors and cause strong over-regulation. This over-regulating property is essential, as has already been said, if a rapid regulating effect is to be produced; it must, however, be completed by a recall device to avoid hunting. This elastic recall device is composed of the recall spring proper q and of a damping device which follows the movements of the motive system with a certain lag. The recall spring forms a flexible connection between the rotating drum c and the damping sector p which gears with the pinion on the damping disc o. This aluminium disc rotates between the poles of the permanent magnets m which have a retarding effect on its movement.

The process of regulation is easily followed with the help of the drawing in Fig. 6, which is to be considered as purely diagramatic. We will assume that the alternator is fully loaded, and that it requires excitation at 100 volts to maintain its pressure. Under these conditions, the contact points of the sectors are so situated that the pointer z is about on position 1 of the scale; that is to say, the regulating resistance is nearly all short circuited. As long as the alternator pressure remains constant, the torque on the drum counterbalances the torque produced by the main spring f. These conditions change immediately if the load be reduced, the current delivered being diminished by half, for example. The alternator pressure rises and with it the torque on the drum c. This torque becomes stronger than that of the spring and produces a clockwise rotation of the motive system. At first this movement is unhindered, but gradually the recall spring is tightened between the motive system and the damping segment which can only follow slowly.

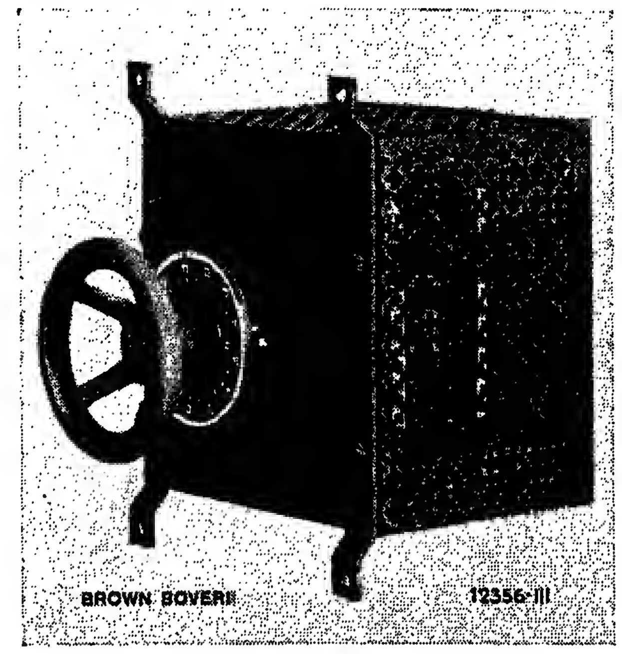


Fig. 7. — Adjusting rheostat, Type H4/1, to be built-in behind the switch panel.

A counter torque on the drum c is thus produced which brings the motive system to a stop in position 3, for example. In the meantime, the excitation pressure has responded to the movement of the point of contact and is now reduced to about 50 volts. The pressure of the alternator reaches the value corresponding to this excitation pressure after a certain lapse of time, owing to the electro-magnetic inertia of the set, following which the torque on the drum diminishes. The counter torque of the tightened recall spring outweighs that on the drum c and causes a return movement of the motive system. In position 2, for example, equilibrium is again established; the exciter pressure is now 70 volts and corresponds to the new load conditions under normal alternator pressure. The regulating mechanism therefore remains steady in this position.

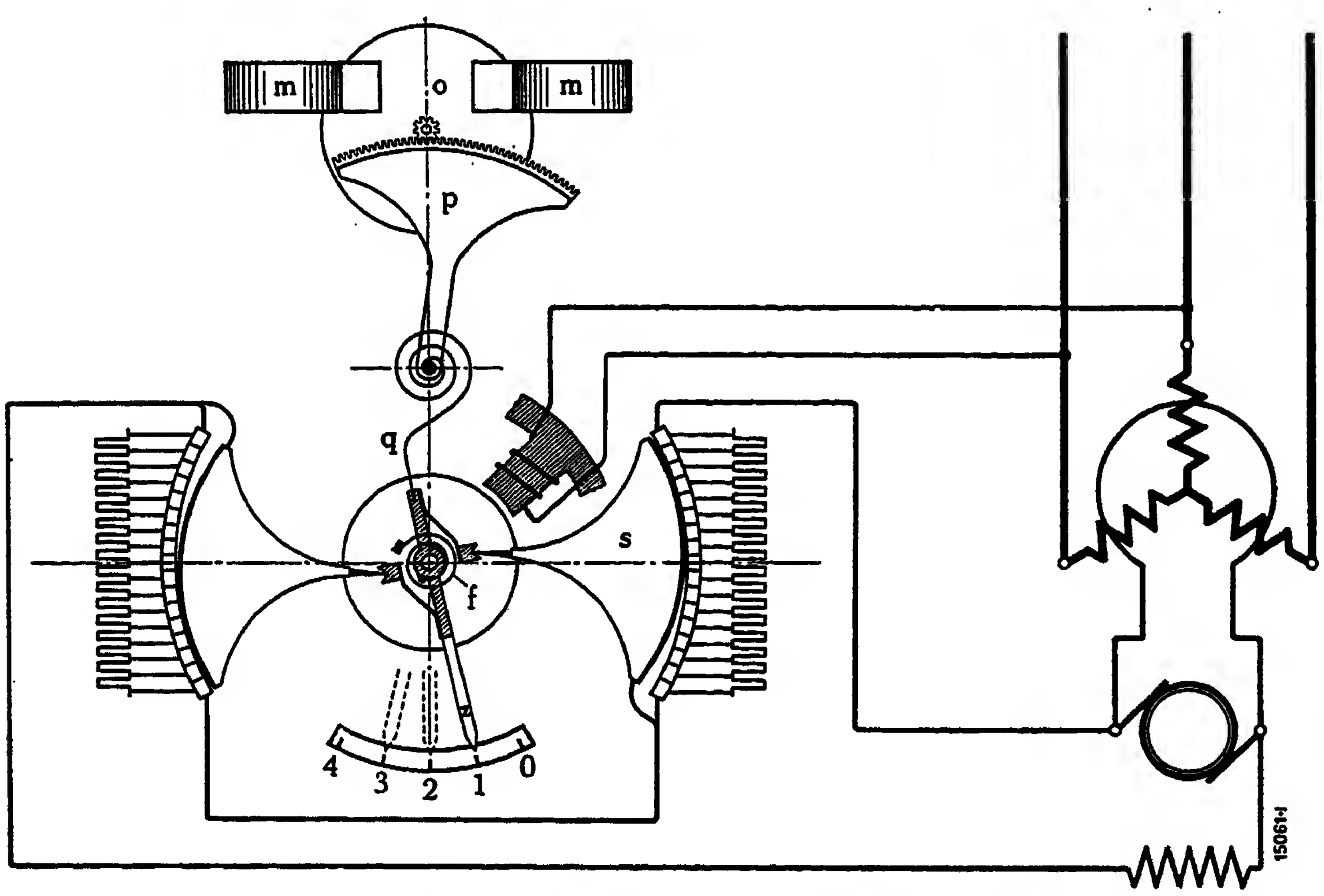


Fig. 6. — Diagram illustrating the regulating process.

The simplicity of the recall device and the ease with which it can be adjusted, by displacing the damping magnets, allow of setting the regulator quickly and satisfactorily for the operating conditions

of machines presenting very varied electro-magnetic properties.

3. ADJUSTMENT.

The regulator is set for the service pressure required, by means of the worm r (Fig. 4), which modifies the tension of the main spring f by rotating through a certain angle the housing to which the outer extremity of that spring is secured. It is thus possible to set the regulator for a pressure which varies by $\pm$ 6 % from the original setting of the apparatus, without affecting the accuracy of the regulation to any appreciable extent.

If the apparatus be required to have a still bigger range of adjustability or if the service conditions call for frequent changes of pressure, a small adjustable resistance H 4/1 is delivered with the apparatus (see Fig. 7). This resistance is designed for mounting in the switchboard and is adjusted by means of a small handwheel.

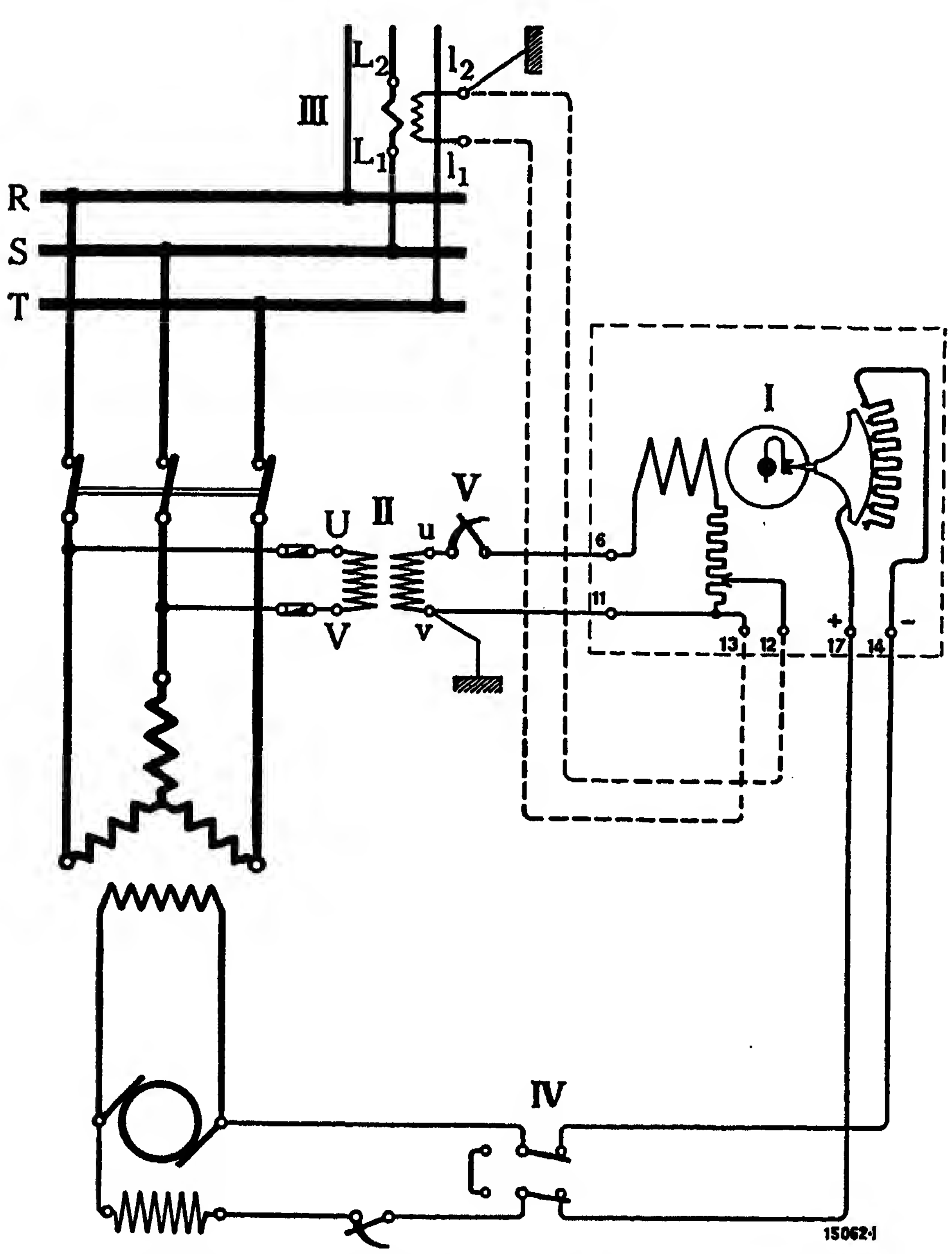


Fig. 8. — Diagram of connections for the automatic pressure regulation of one three-phase alternator working alone.

I. Quick-acting regulator.*
II. Pressure transformer with fuses.
III. Current transformer for compounding.
IV. Excitation change-over switch.
V. Adjusting rheostat.

4. COMPOUNDING.

In many systems, the power station is at a great distance from the principal centres of power consumption, so that a considerable pressure drop in the transmission line must be reckoned with. It would, therefore, be a mistake to regulate to constant pressure at the power station. On the contrary, the pressure in the power station must be caused to rise and fall with the increase or decrease of the load, in order that the pressure may remain constant at the centre of distribution.

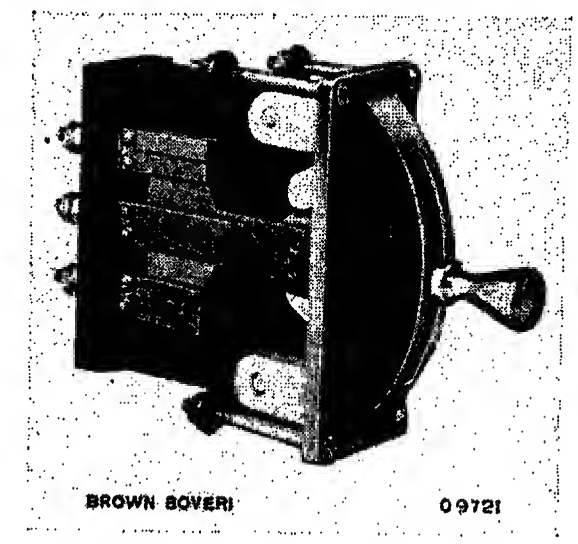


Fig. 9. — Excitation change-over switch.

This result is obtained by compounding the regulator (see Fig. 8), with which object a current transformer is inserted in the circuit of the busbars or of the outgoing mains, the secondary terminals of the transformer being connected to terminals 12 and 13 of the regulator. The secondary or compounding current is led through an adjustable section of the compounding resistance u′ (Fig. 4). The current of the motive system proper and the compounding current are superposed in this resistance in such a manner that, when the latter increases, the electromagnetic torque decreases and the contact sectors are displaced until the alternating pressure reaches a correspondingly higher value.

In this way, compounding can be adjusted up to about 15 %. If still higher compounding be desired, this can be attained by adding auxiliary compounding resistances outside the regulator.

5. APPLICATIONS OF THE AUTOMATIC PRESSURE REGULATOR.

Most power plants to-day are built to produce alternating three-phase current. All the following diagrams of connections are, therefore, intended for such plants, although the same diagrams can be used for single and two-phase plants also by making certain changes.

Fig. 8 shows the simplest example encountered in practice, namely, one alternator working alone. The pressure and current transformers shown can be omitted under certain circumstances; for instance,

the pressure transformer will be dispensed with if the operating pressure of the plant be under 250 volts. The adjusting resistance shown can also be left out if frequent changes in pressure are not called for.

As the pressure regulator produces the necessary excitation automatically, the setting to work and

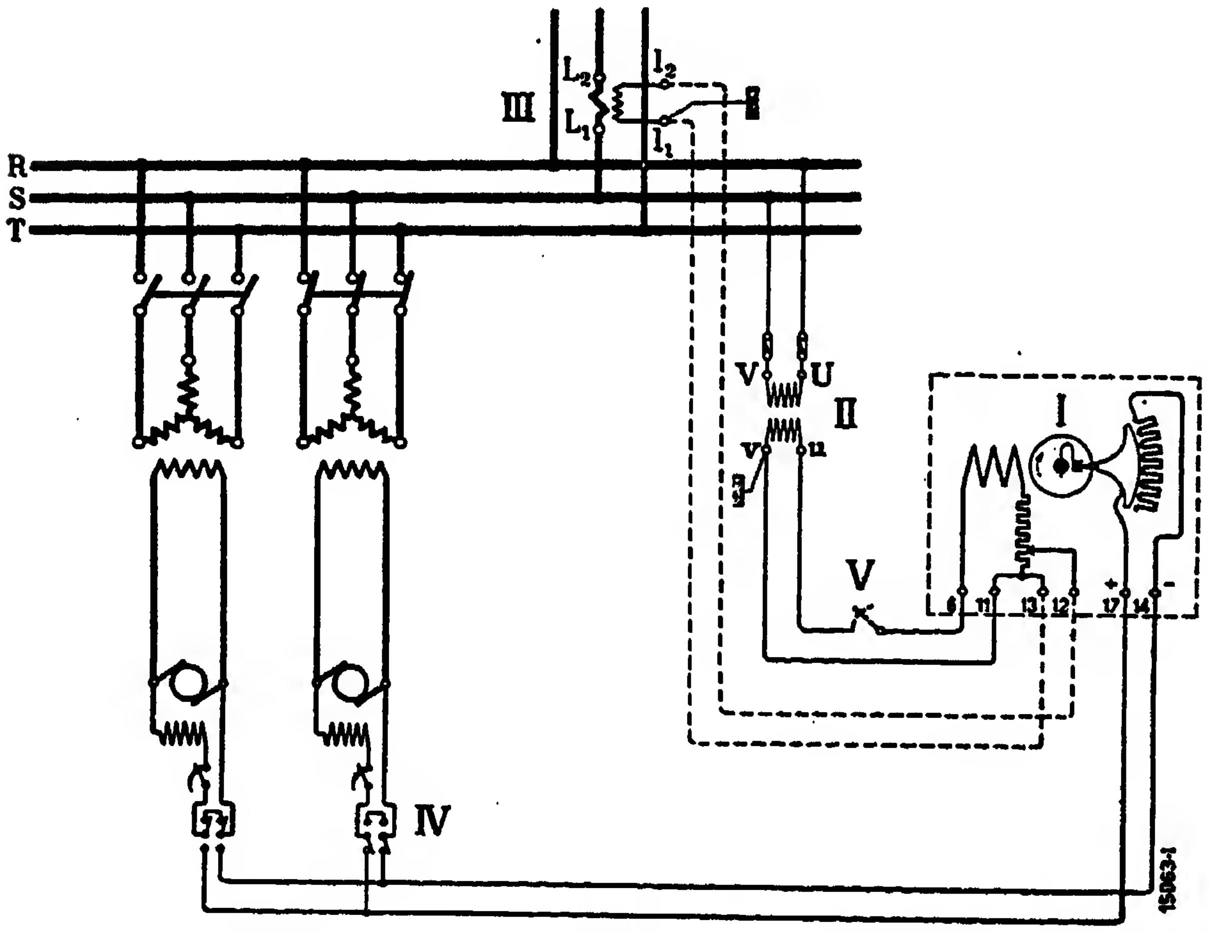


Fig. 10. — Diagram of connections of pressure regulator serving several alternators alternately.

cutting out of the alternator can be effected without the operator having to interfere with the regulation. The pressure regulator always remains connected to the machine and thus forms a reliable safeguard against excess pressures when the generator is cut out owing to some disturbance on the system. If, for any reason, the operator desires to change over from automatic to hand regulation, the excitation change-over switch is used (Fig. 9).

If several sets work in parallel in a power station, it is true that, if only a certain number of the generating units were equipped with automatic regulators, the pressure would still be kept constant.

In this case, means must be provided to allow of changing-over a regulator from one alternator to another, or rather from one exciter to another (see Fig. 10). To prevent more than one exciter being connected to the regulator at a time, which would cause the regulator contacts to be overloaded, only one handle is delivered

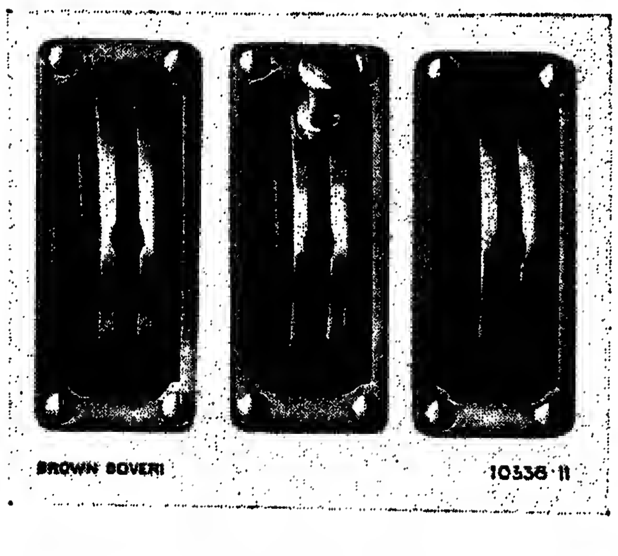


Fig. 11. — Change-over switches with removable handle.

for the change-over switches of the several generating sets. This handle is removable but can only be taken out of the switch when it is in the "cut-out" position (see Fig. 11). The use of one regulator for several machines has the disadvantage that, when load fluctuations occur, the wattless current is unequally distributed between the various units. Thus, if all the

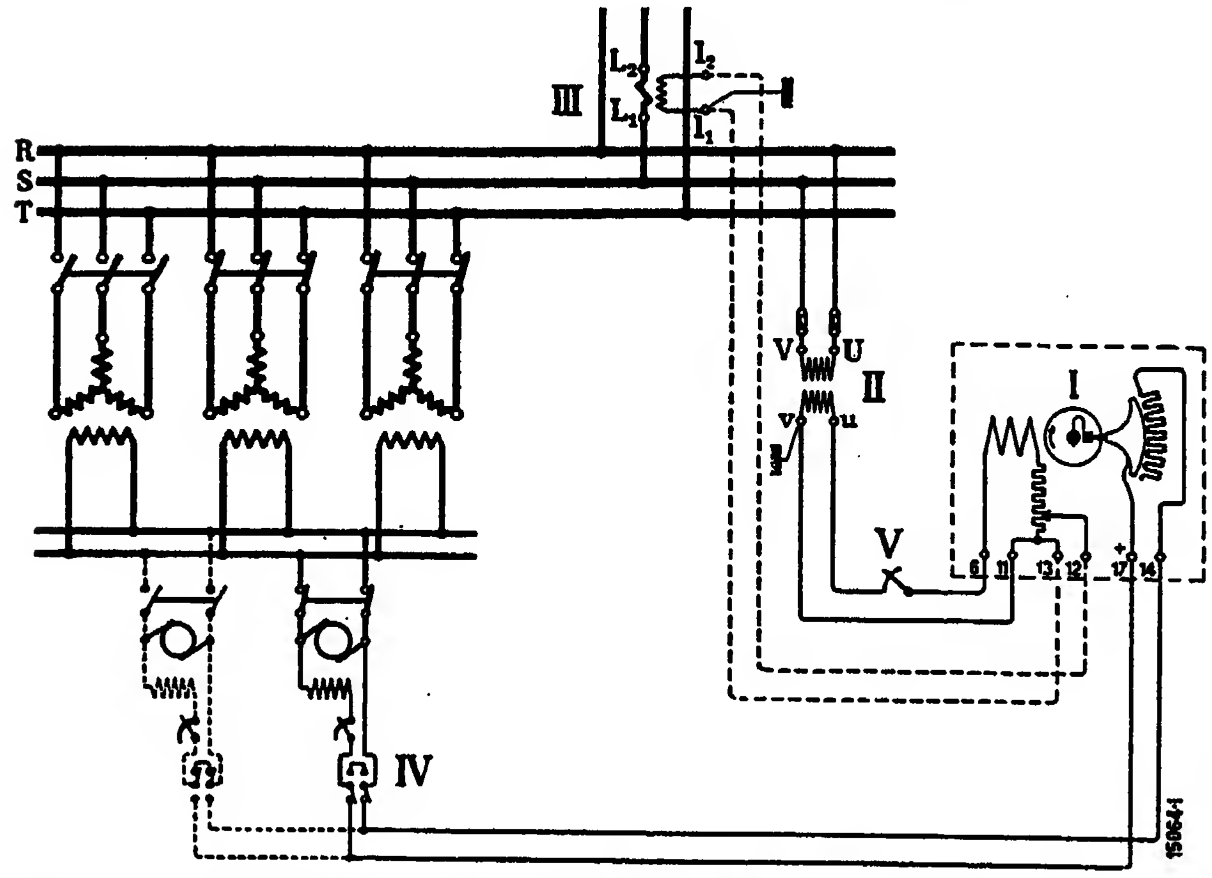


Fig. 12. — Diagram of connections of pressure regulator for three-phase alternators with common exciter.

alternators are required to operate with the same power factor, it is absolutely necessary that some further hand regulation be carried out by the switchboard attendant, on those which have no automatic regulators.

Another condition which must be fulfilled if one regulator be used for several sets, is that the shunt current of the various exciters and the magnetic characteristics of the sets do not differ too much from one another, so that the regulator is capable of operating in a satisfactory manner with each. The limitations which are thus imposed on the use of one regulator common to several alternators have resulted in the provision of each set with its own regulator, in cases where several are running in parallel. In this way, the work of the attendant is simplified and the reliability of operation is considerably increased. An essential condition is, of course, that each alternator be provided with its own exciter.

In old plants equipped with *central excitation* where it is impossible to provide each set with its own automatic regulator, the arrangement with a common regulator as shown on Fig. 12 must be adopted.

In up-to-date stations with *individual excitation* of the alternators the only rational solution is to provide

each with its own regulator. When machines are working in parallel, it is not possible, however, simply to make the motive systems of the regulators dependant on the pressure alone. On account of the neutral equilibrium of the motive system of the regulators, it can happen that the currents delivered by the individual alternators vary very much one from another, without influencing the pressure regulators. Very slight inequalities in the setting of the regulators might cause such differences in the power factors of the sets working in parallel — and consequently the setting up of such considerable exchange currents—that the automatic oil switches would open. It is, therefore, necessary to make the motive systems of the regulators subject, not only to the pressure, but also to the current of the various alternators, in order to assure an even load distribution among the various sets in parallel. If, however, this influencing of the regulator by the current is to be without influence on the supply pressure, it must obviously only come into play when an unbalanced distribution of current occurs and must cease when equilibrium has been re-established. *The polygon of stabilisation* is used for this purpose.

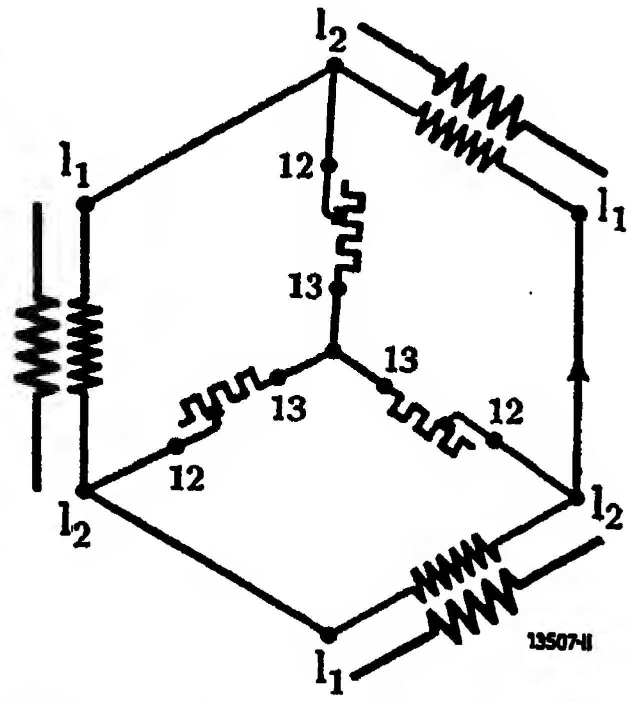


Fig. 13. — Diagram of the polygon of stabilisation.

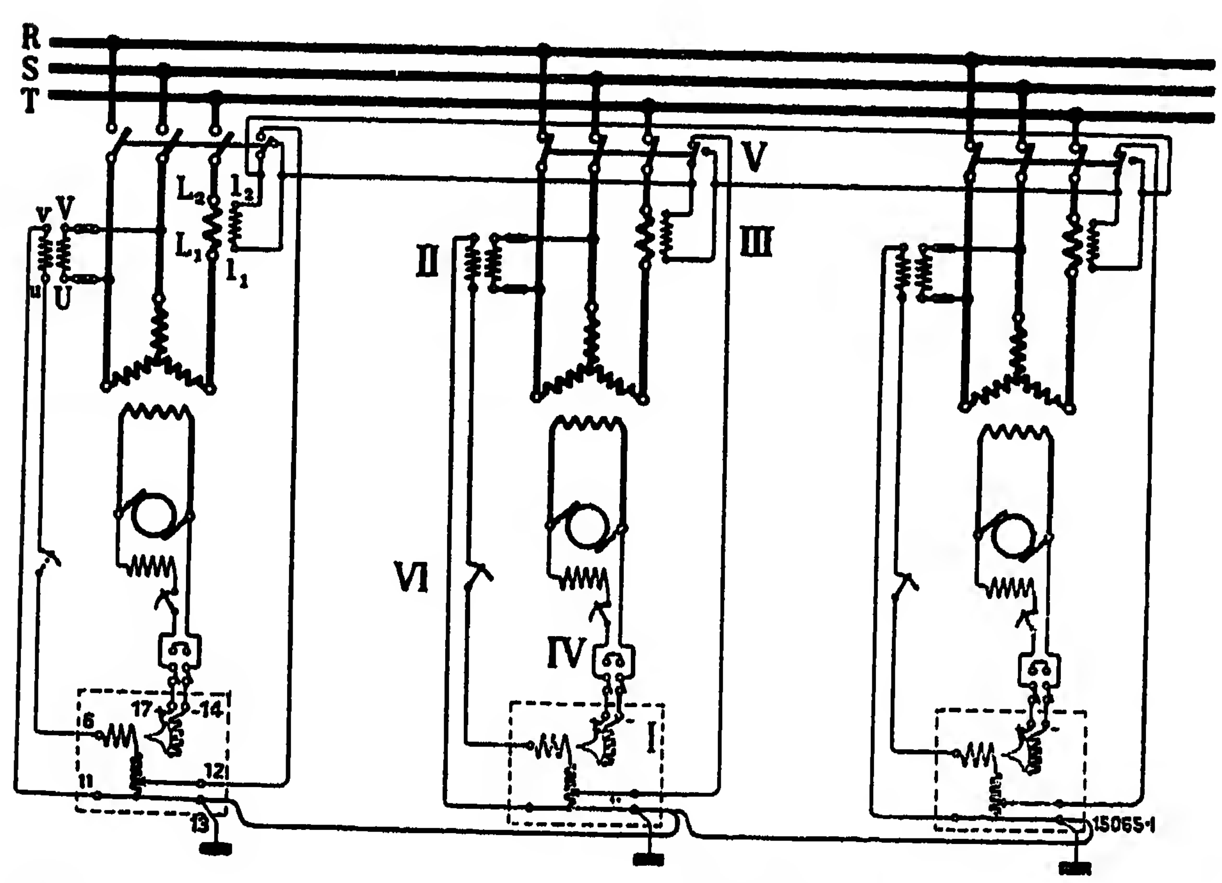


Fig. 14. — Diagram of connections of pressure regulators for three-phase alternators running in parallel (Polygon of stabilisation).

I. Pressure regulator.
II. Pressure transformer.
III. Current transformer.
IV. Excitation change-over switch.
V. Change-over contact.
VI. Adjusting rheostat.

Fig. 13 shows the polygon, purely diagramatically, while Fig. 14 shows its practical application and the necessary connections. A current transformer is inserted in one phase of each alternator. The secondary windings of these current transformers are connected in series so as to form what is termed the polygon of stabilisation, while the apexes of the polygon are connected to a common point through the resistances u′ of each regulator, already mentioned when compounding was discussed.

If, now, even distribution of current exists, the secondary coils of the current transformers deliver currents identical in phase and intensity. The apexes l_2 of the polygon are, therefore, at the same potential and no current flows from them towards the middle point. This state of things changes, immediately however, if any one alternator begins to work at a power factor different from the others, that is to say, delivers more or less current than the value corresponding to its kilowatt load. Pressure differences will then arise and exchange currents begin to flow between the apexes l_2 of the polygon. These currents are superposed on the current proper of the motive system, and exercise a positive or negative influence on the torque of the regulator similar to that produced by compounding. The contacts of the regulator are, therefore, displaced up to the point where even current distribution is again established. As a result of the phase displacement of the stabilisation current with regard to the current proper in the winding of the motive system, inequalities among the different watt currents have small influence on the regulator. Thus, up to a certain point, the alternators can be made to deliver unequal watt loads if desired; in short, the polygon of stabilisation is mainly sensitive to fluctuation of the wattless current.

In order that the switchboard operator should not be obliged to take special measures when a set is put into, or out of operation, the secondary windings of the current transformers are connected to the polygon of stabilisation through change-over contacts placed on the shafts of the different oil switches. In this way, when an alternator is switched in or out, its current transformer is automatically switched into or out of the polygon of stabilisation.

When it is required that alternators working in parallel should not only be equipped with the stabilising device formed by the polygon but be compounded

as well, to compensate for a tension drop on a long line, the resistances u′ are used for the purpose. In this case, small auxiliary current transformers are used to produce the stabilising effect. These are connected

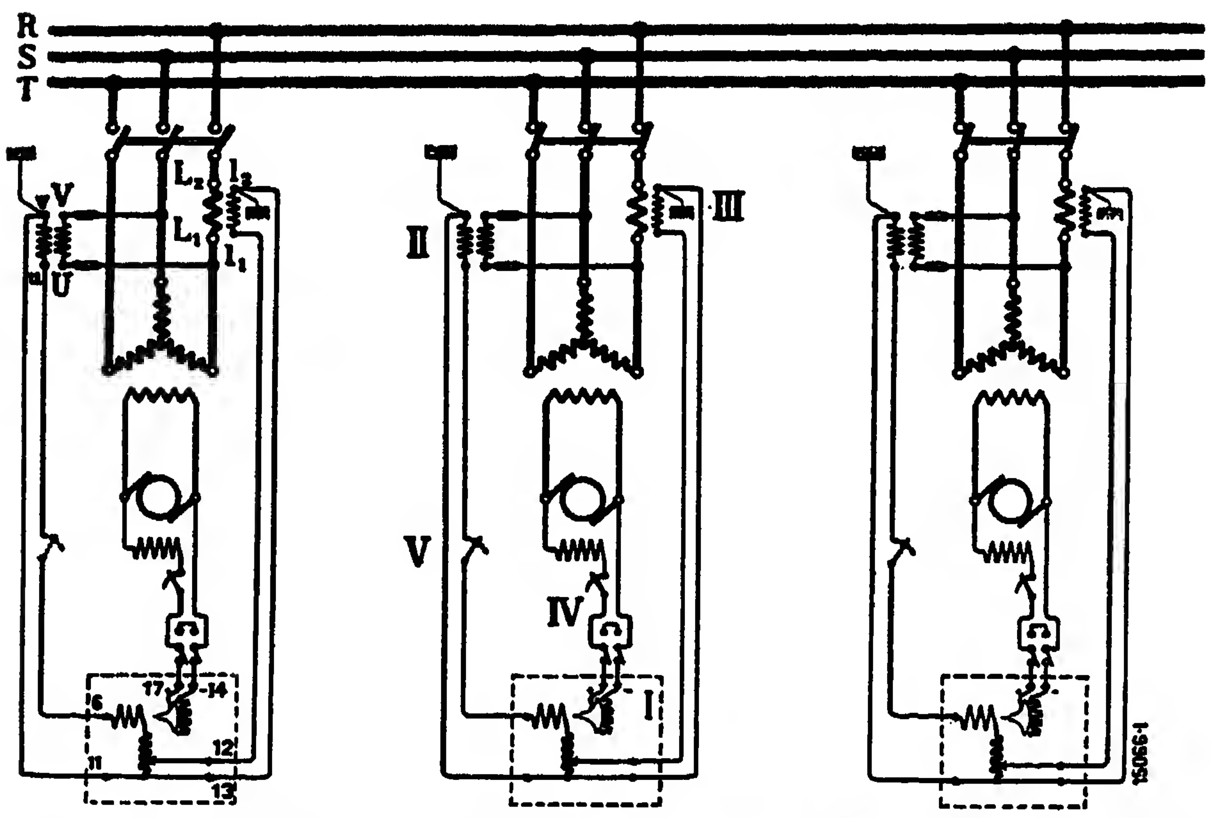


Fig. 15. — Diagram of connections of pressure regulators for three-phase alternators running in parallel (regulators with static characteristics).

I. Pressure regulators.
II. Pressure transformers.
III. Current transformers.
IV. Excitation change-over switch.
V. Adjusting rheostat.

so that one winding is in the circuit of the motive system and the other in the leads to the centre of the polygon, in place of the resistances u′.

The polygon can, of course, only be used for sets in the same station. If the machines are in different places, the length of the interconnecting conductors would be too great. In this case, the method described below must be employed.

When the apparatus was described on page 5, it was indicated how the torque produced by the main spring could be compensated by the auxiliary spring so that the pressure of the generator remained exactly the same whatever the position of the regulating mechanism—i. e., whatever the load. As mentioned before, without the help of a stabilising device this astatic regulator is not stable when working in parallel with others. Stabilisation of the regulator for operating in parallel can, however, be attained, without the help of the polygon if the falling characteristic of the main-spring torque accompanying an increase in excitation is not completely compensated. The equilibrium of the motive system is then stable instead of being neutral. A regulator having these properties is said to be a *static regulator.*

Static regulators have, of course, the defect that when the load of the generating set increases, producing a movement of the regulating mechanism of the quick-acting regulator to reinforce the excitation, the original operating pressure is not exactly re-established. The value obtained remains somewhat below the original pressure until the former load is again reached. Similarly, a partial unloading of the alternator results in a slightly higher pressure. This inaccuracy would make the static regulator useless in many cases, if its falling characteristic could not be compensated. This compensation is obtained by means of the so-called compensating current transformer (see Fig. 15). This current transformer has its primary winding in one of the alternator leads and its secondary connected to the regulator through terminals 12 and 13. As in compounding, it influences the motive system in the sense of pressure increase, so that, by properly adjusting its effect, the pressure will remain constant from no load to full load, and the static character of the regulator is completely compensated.

It would seem as though the same regulating effect were obtained as with an astatic regulator, while there is in reality a fundamental difference between the two modes of regulation. The effect of the compensating current transformer does not only depend on the value of the current delivered by the alternator but also on the phase angle between pressure and current, in other words, on the power factor. When the current lags very much on the pressure, the compensating effect will be insufficient; when the power factor is near unity, or even if the current leads on the pressure, the compensating effect is superior to the pressure drop caused by the static characteristic of the alternator. The pressure thus remains constant from no load to full load, only for a given value of the power factor, which can be adjusted. The influence of the power factor on the pressure regulated is such that, when the power factor tends to diminish, the quick-acting regulator decreases the pressure, and increases it when the power factor tends to improve. In this way, when alternators are in parallel, each quick-acting regulator tends to maintain constant the power factor of the machine to which it belongs, in other words, to make for balanced distribution of the wattless current among the alternators. For the above reasons, *a special stabilising device is not required when static regulators are used.*

The static regulator is used to advantage in plants where no connection at all can be made between the alternators, or where they can only be established at great inconvenience. This is the case when machines are in plants situated in different localities, or when they have to work on any one of several busbar systems, which, with polygon connection, would mean subdivision into a number of polygons and the use of special changeover switches.

From the description given above, it can be gathered that the accuracy of pressure regulation with a static regulator does not attain that of the astatic type. The latter regulates to constant pressure independently of fluctuations in load or speed, which the static regulator does not. Nevertheless, the inaccuracy inherent to regulation by a static regulator is, as a rule, so unimportant in practice that, to-day, preference is often given to this type. The static regulator is especially valuable in the case of parallel operation between several power stations. The direction and value of the flow of energy between the power stations may change according to the season, and in such a case it is necessary for the regulators to give, not constant pressure in all the stations, but pressure varying automatically in such a way that the station delivering energy always works at a higher pressure than the one to which it delivers it. In this way, unnecessary exchange currents are avoided and the power factor is kept practically uniform. Only static regulators fulfil this condition.

Very often, when several plants work in parallel, both astatic and static regulators are used. The station nearest the principal centre of power consumption is considered as leading station and is equipped with astatic regulators which keep the pressure constant there. The other power stations in parallel with the first are equipped with static regulators and, therefore, automatically take over such a portion of the wattless load that the exchange or compensating current between the plants is reduced to a minimum.

By using static regulators with adjustable resistances as mentioned on page 6, individual machines can, if required, be made to deliver wattless current only; that is to say, they can be made to work as phase compensators. The static regulator, while assuring the desired phase compensation, gives stable parallel operation of the unit in question with the other alternators.

From the point of view of regulation proper, the static regulator possesses a great advantage over the astatic type, which has been in general use for pressure

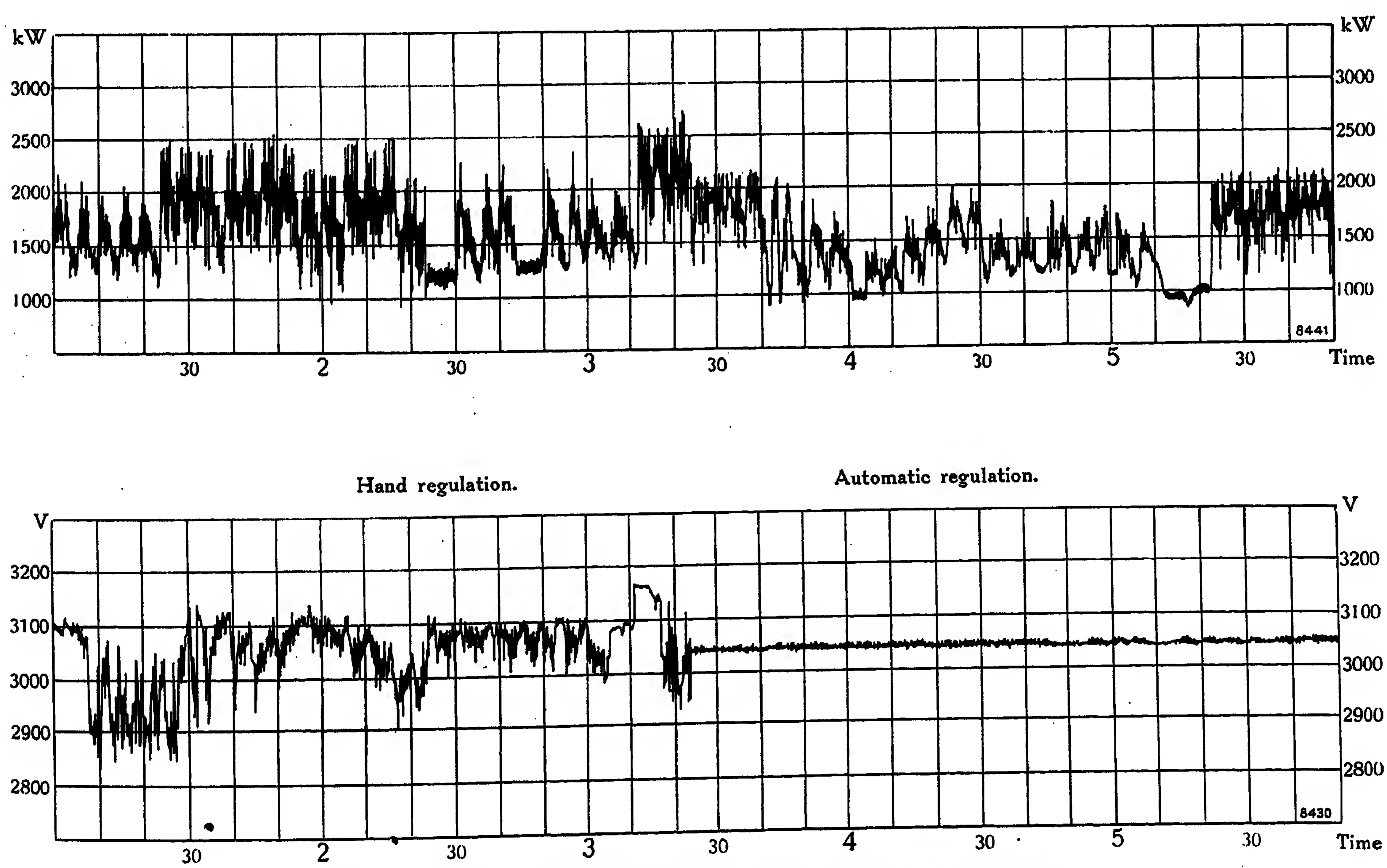


Fig. 16. — Load and pressure curves recorded on a local supply system.